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3

NOVA-LIKE VARIABLES

I. DEFINITIONS AND GENERAL CHARACTERISTICS*

ABSTRACT: On grounds of different observable characteristics five classes of nova-like objects are distinguished: the UX Ursae Majoris stars, the anti-dwarf novae, the DQ Herculis stars, the AM Herculis stars, and the AM Canum Venaticorum stars. Some objects have not been classified specifically. Nova-like stars share most observable features with dwarf novae, except for the outburst behavior.

There has always been a common understanding of what constitutes a dwarf nova, even though the terminology was subject to many changes. A corresponding agreement cannot be found for the nova-like stars. Many objects which are now classified as "nova-like," were in earlier times simply regarded as irregular variables. For some of them, like V Sge (Ryves, 1932; Payne, 1934), AE Agr (Schneller, 1954; Crawford and Kraft, 1956), or MV Lyr (Walker, 1954a; Greenstein, 1954, similarity to novae or dwarf novae was noted. Others like AM Her (Schneller, 1957) were classified as Mira variables, RW Aurigae stars, flare stars, or other types of stars. Similarly, since for a long time the name "nova-like" was taken literally, this term was used for objects which in the modern use of the word clearly must not be classified under this name; P Cygni stars and symbiotic stars were included particularly often (e.g., Vorontsov-Veljaminov, 1934; Glasby, 1968). In his review on cataclysmic variables, Warner (1976) equates the terms "nova-like variable" and "UX Ursae Majoris star," which, in contrast to the literal meaning of the word, already comes close to the modern definition.

Many more observations, more refined observing techniques, and in particular the availability of UV and X-ray data brought about an enormous increase in the number of detected nova-like stars during the last 10 to 15 years, but the need also became obvious for a more diversified classification scheme. The definition of what constitutes a nova-like variable was a very controversial issue until the use of this expression was restricted to cataclysmic variables (understood in the modern sense).

All *nova-like variables* have some properties in common: they do not show large outburst activity (though they may be found in "high" or "low," "on" or "off" states), so they are neither novae nor dwarf novae, but in one way or another they look like a dwarf nova in some stage of activity. The bulk of their observable features is in agreement with the assumption of the Roche model for the explanation of the underlying physical nature. The range of variability they display is considerable.

Five classes of nova-like stars are distinguished: the UX Ursae Majoris stars, the anti-dwarf novae, the DQ Herculis stars, the AM Herculis stars, and the AM Canum Venaticorum stars; and some systems are just classified as nova-like when they cannot be attributed to either of the former classes.

*In the following, whenever they exist, variable star names will be used according to Kukarkin's catalogue, rather than the names of objects involving their coordinates; cross-correlations between names are given in the index list.

The spectra of UX Ursae Majoris stars look very similar to those of dwarf novae at some stage of the outburst cycle. They may show emission or absorption lines, or both, often with wide absorption shells underlying strong emission lines. The appearance of a spectrum can be variable. Photometric variations are within narrow limits, of typically 1 mag or less, and do not follow any regular patterns.

The anti-dwarf novae got their name from the appearance of their light curves: usually they are found in a bright state, indistinguishable from UX Ursae Majoris stars; at times, however, their brightness drops by several magnitudes for extensive periods of time, rendering them similar to dwarf novae in the minimum state. The drop in brightness seems to happen at random. Thus it is quite possible that more stars of this subclass are hidden among the UX Ursae Majoris stars. An alternative name for these stars is VY Sculptoris stars, after the name of one of its members.

DQ Herculis stars, or "intermediate polars," cannot be readily distinguished from the UX Ursae Majoris stars, either spectroscopically or in their long-term behavior. When observed photometrically with high time resolution, however, they are found to show extremely stable pulsations of high coherence and with periods of many minutes; and even more than one such periodicity can be exhibited at a time.

AM Herculis stars, or "polars," are characterized by a very high optical polarization synchronous with the binary period. In addition, they exhibit strong high-amplitude flickering. The spectrum is dominated by strong narrow emission lines.

AM Canum Venaticorum stars are characterized by the absence of any hydrogen lines, but they show strong lines of helium, the strengths and profiles of which are quite unlike those of single He white dwarfs. In addition they show flickering activity.

GENERAL INTERPRETATION: The understanding is that dwarf novae, UX Ursae Majoris stars, and anti-dwarf novae are basically the same sort of objects. The difference between them is that in UX Ursae Majoris stars the mass transfer through the accretion disc always is high so the disc is stationary all the time; in anti-dwarf novae for some (unknown) reason the mass transfer occasionally drops considerably for some time, and in dwarf novae it is low enough for the disc to undergo semi-periodic changes between high and low accretion events. DQ Herculis stars are believed to possess weakly magnetic white dwarfs which disrupt the inner disc at some distance from the central star; the rotation of the white dwarf can be seen as an additional photometric period. In AM Herculis stars, a strongly magnetic white dwarf entirely prevents the formation of an accretion disc, and at the same time locks the rotation of the white dwarf to the binary orbit. Finally, AM Canum Venaticorum stars are believed to be cataclysmic variables that consist of two white dwarf components.

II. UX URSAE MAJORIS STARS

II.A. PHOTOMETRIC OBSERVATIONS

II.A.1. PHOTOMETRIC CHANGES ON ORBITAL TIME SCALES

ABSTRACT: The photometric appearance is very similar to that of dwarf novae in exhibiting flickering, humps, and eclipses, and in the related color dependences. The eclipsing systems are remarkably similar to each other in appearance. Unlike in dwarf novae, the hump maximum can occur before as well as after the eclipse.

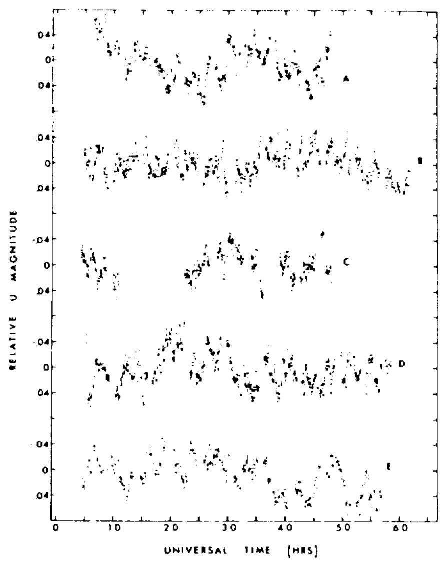
other nova-like stars: 103, 113, 114, 117, 119, 122, 125, 140

dwarf novae: 35, 46

interpretation: 172, 177, 190, 194

UX Ursae Majoris stars are distinct from dwarf novae only in that they do not show any semi-regular outburst activity. However, in some systems the brightness can increase or decrease irregularly on time-scales of years, by about one magnitude (Figure 3-1), but the star's photometric or spectroscopic appearance is not significantly affected by this.

a)



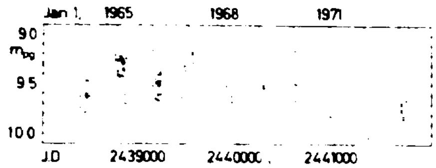


Figure 3-1. Long-term variations of IX Vel (Wargau et al, 1984).

b)

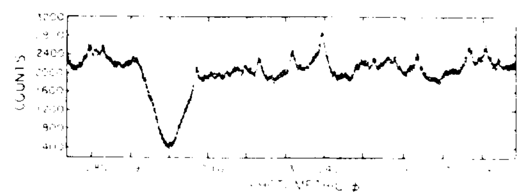
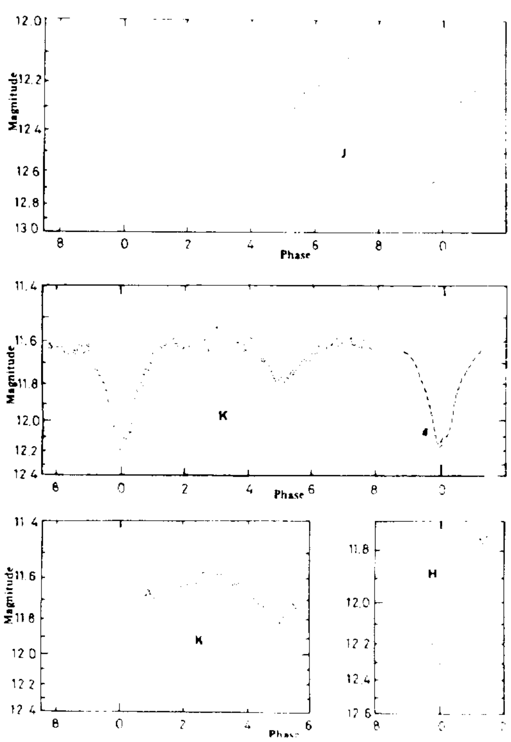


Figure 3-2. Typical orbital light curves of UX Ursae Majoris stars: a) SW Sex (Penning et al, 1984); b) IX Vel (Williams and Hiltner, 1984).



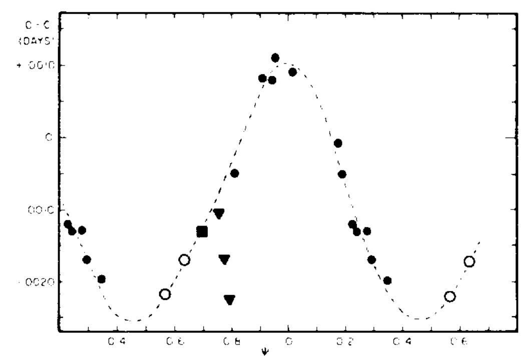


Figure 3-4. Secular period variations in UX UMa (Quigley and Africano, 1978).

Figure 3-3. (left) IR light curves of RW Tri (Longmore et al, 1981).

The orbital light curves are indistinguishable from those of dwarf novae in showing more or less pronounced flickering and, possibly, humps (Figure 3-2a). There can be appreciable changes in the appearance of the light curve from cycle to cycle, even, in the case of SW Sex, including occasional irregular flare activity (Penning et al, 1984).

Some of the objects (like UX UMa, RW Tri, SW Sex, LX Ser, V363 Aur) show eclipses in their light curves (see Figure 3-2b; see also, e.g., Figure 4-1 and Johnson et al, 1954 for UX UMa; Africano et al, 1978 and Horne and Stiening, 1985 for RW Tri; and Horne et al, 1982 for V363 Aur). All these eclipse light curves look surprisingly similar to each other and also to the light curves of dwarf novae in outburst (see e.g., Figures 2-28, 2-16, 2-52) in being noticeably asymmetric, in changing the slope of ingress shortly after the first contact, and most notably, in normally having a pronounced, though highly variable, hold at egress; the bottom usually is rounded. In all objects a hump is at times visible, at other times it is absent. In RW Tri and UX UMa the hump maximum can occur before as well as after the eclipse. When UX UMa exhibits a hump, the system's brightness decreases steadily after hump maximum until the next hump starts; there is no phase of constant light (see Figure 4-1); this effect is the more pronounced the shorter the wavelength. From an extensive investigation of RW Tri, Walker (1963) found that the eclipse is the deeper and starts the later the fainter is the system's brightness. Color changes during eclipse in RW Tri are the same as in dwarf novae in the sense that the system becomes bluer in (U-B) and redder in (B-V). V363 Aur on the other hand becomes redder in both colors during eclipse (Horne et al, 1982). RW Tri has been observed photometrically at IR wavelengths. A secondary eclipse of 0.4 mag in K centered about phase 0.5 is clearly visible in J and K (Figure 3-3). The widths of primary and secondary eclipses are the same, both lasting for some 80 minutes. In UX UMa no secondary minimum can be detected in J and K (Frank et al, 1981).

The eclipse timings are very strictly periodic, although for RW Tri and UX UMa (like in several other cataclysmic variables — see e.g., Chapter 2.II.B.5) a small cyclic secular variation of this timing has been found (e.g., Figure 3-4); whether or not these are periodic is still controversial (Mandel, 1965; Africano and Wilson, 1976; Kukarkin, 1977; Africano et al, 1978; Quigley and Africano, 1978).

Polarimetric observations were carried out for UX UMa (Szkody et al, 1982a). They revealed an insignificant polarization of 0.30 ± 0.10%, which lies in the range observed for dwarf novae. For SW Sex an upper limit of 0.15% in circular polarization was obtained (Penning et al, 1984).

II.A.2. FLICKERING AND OSCILLATIONS

ABSTRACT: Rapid monochromatic coherent oscillations are occasionally present. The periods are slightly variable but no simultaneous, overall brightness changes occur in the system.

other nova-like stars: 106, 113, 117, 121, 122, 128, 141

dwarf novae: 54, 56

interpretation: 151, 181, 185, 213

On time-scales of minutes all UX Ursae Majoris stars show pronounced flickering with amplitudes between several hundredths and some tenths of a magnitude, with a tendency for the amplitude to be larger at shorter wavelengths, as it is observed in dwarf novae. Observations of RW Tri show that the flickering disappears entirely in all colors between phases −0.04 and +0.04 with respect to central eclipse (the photometric eclipse itself lasts from phase −0.07 to +0.07), showing that (1) whatever the source of flickering may be, it is centered on the main eclipsed source, and, (2) flickering obviously is not directly related to the source of the hump, since in these particular observations the hump followed the eclipse, (Horne and Stiening, 1985).

Rapid coherent oscillations with periods on the order of 30 sec have been detected in UX UMa (Nather and Robinson, 1974) and V3885 Sgr (Warner, 1973). Their characteristics are very similar to those of coherent oscillations seen at times in dwarf novae during outburst.

They are not always present; they have been seen twice in UX UMa for some nights, while several weeks later they had disappeared. When they are present, the power spectra show one single sharp spike and no harmonics, but slowly, on time-scales of days, the period drifts to either longer or shorter values; whether this is a cyclic behavior or not is not clear (Nather and Robinson, 1974). No conspicuous brightness changes of the system comparable to changes of dwarf novae in outburst are reported to have occurred along with the period changes. In UX UMa, a phase shift of $-360°$ was seen to occur during primary eclipse, just as in dwarf novae (Nather and Robinson, 1974).

II.B. SPECTROSCOPIC OBSERVATIONS

ABSTRACT: In the optical as well as in the UV, this class of stars exhibits the full range of appearances known from dwarf novae at all stages of activity, i.e., ranging from pure emission to almost pure absorption spectra. Pronounced changes in the appearance of one object over longer times are known to occur. Appreciable changes can also be connected with the orbital motion.

other nova-like stars: 107, 116, 119, 122, 124, 134, 141

dwarf novae: 65

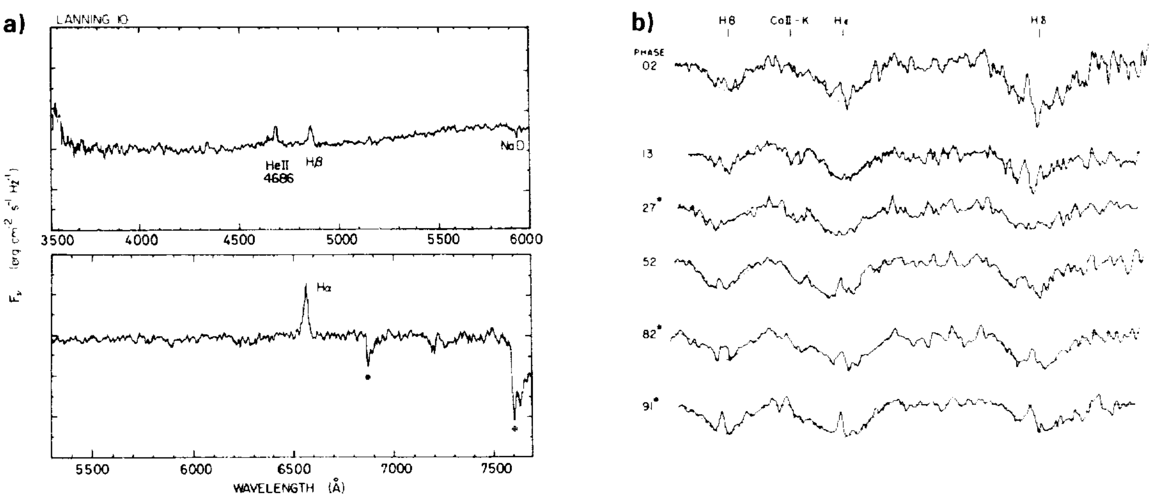
interpretation: 151, 192

Considering the UX Ursae Majoris stars as a group, they exhibit a remarkably wide range of appearance in their optical and UV spectra. In the optical they range from pure emission line spectra of hydrogen (sometimes also He I and He II) — but emissions are normally not as pronounced as in dwarf novae — to almost pure absorption spectra. Absorption lines can exhibit either weak or strong emission cores (e.g., Figure 3-5). In the UV the resonance lines of highly ionized elements are often found in absorption, but they just as well can be in emission, as the example of UX UMa demonstrates; even for a single object the appearance of the UV spectrum can be highly variable with time (Figure 3-6). C IV and N V often, though by no means always, show P Cygni profiles with or without an emission component. Not much is known about temporal changes of the spectra on time-scales longer than a few orbital cycles. But as published spectra of RW Tri demonstrate (Williams and Ferguson, 1982; Williams, 1983), considerable changes in the line flux do occur over longer intervals of time (Figure 3-7).

Considering the strengths and profiles of the UV lines, observations show that they are subject to many kinds of strong changes in every single object, changing from being strongly present to entirely absent within weeks — a matter which, however, has so far not been investigated sufficiently. In the case of IX Vel, Sion (1985) investigated the C IV P Cygni profile in particular and found that it is variable within fractions of hours in all its characteristics: the strengths of both absorption and emission components, the position of emission and absorption peaks, and the blueward extension of the absorption wings.

In some systems changes are known to be conspicuous on orbital time scales. For example the observations of RW Tri in Figure 3-7a show pronounced changes in the optical lines as well as in the optical continuum radiation which are related to the eclipse: the continuum becomes considerably redder than it is outside eclipse and, correspondingly, the equivalent widths of the lines increase; some lines are clearly being eclipsed, while others become visible or go into emission only during eclipse. Similar changes have been observed in other UX Ursae Majoris systems (e.g., Williams and Ferguson, 1982; Drew and Verbunt, 1985).

For several objects spectra with a time resolution on the order of 200 sec were obtained (e.g., Kaitshuk et al, 1983; Schlegel et al, 1983; Honeycut et al, 1986), so it was possible to construct light curves for single spectral lines (Figures 3-8). In all these cases the He II light



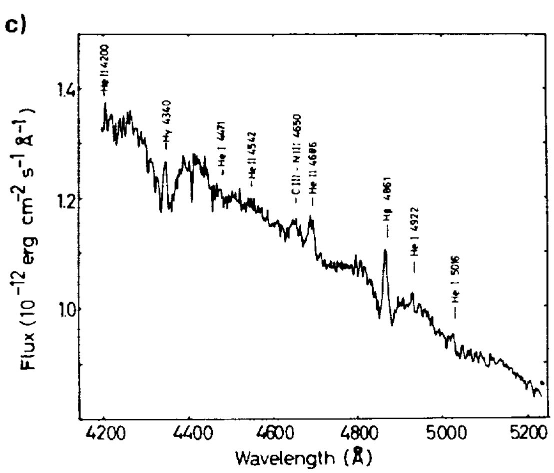


Figure 3-5. Typical optical spectra of UX Ursae Majoris stars: a: V363 Aur, telluric absorption bands are specially marked (Margon and Downes, 1981); b: V3885 Sgr (Cowley et al, 1977); c: IX Vel (Wargau et al, 1983b).

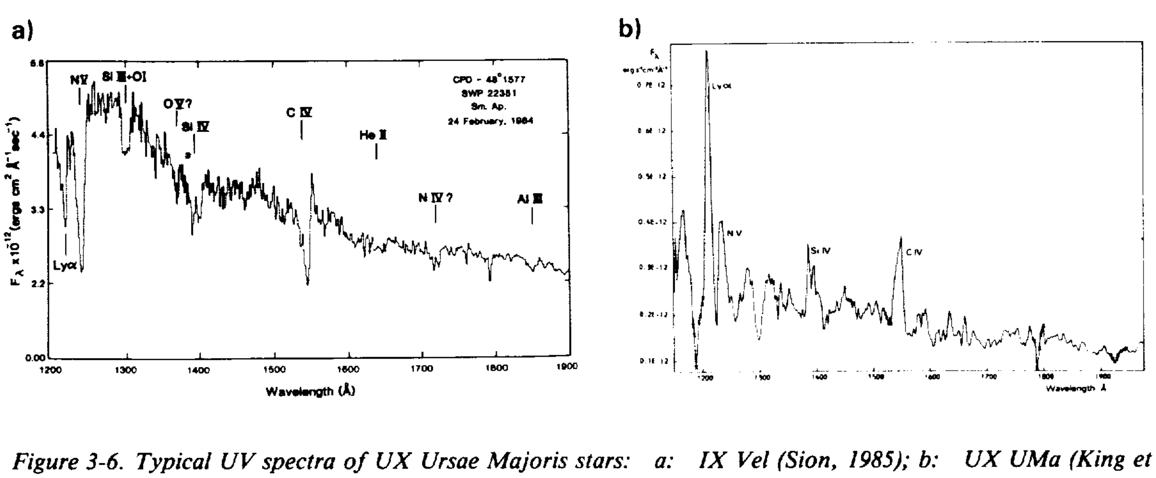
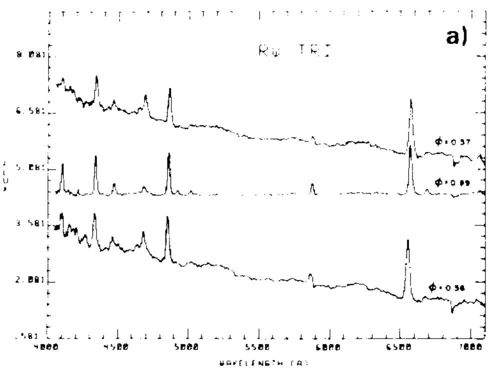


Figure 3-6. Typical UV spectra of UX Ursae Majoris stars: a: IX Vel (Sion, 1985); b: UX UMa (King et al, 1983).



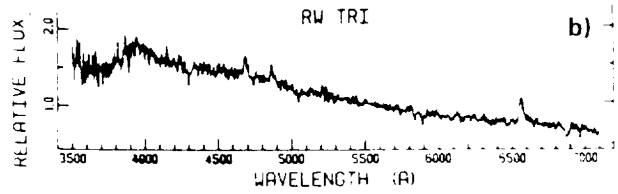
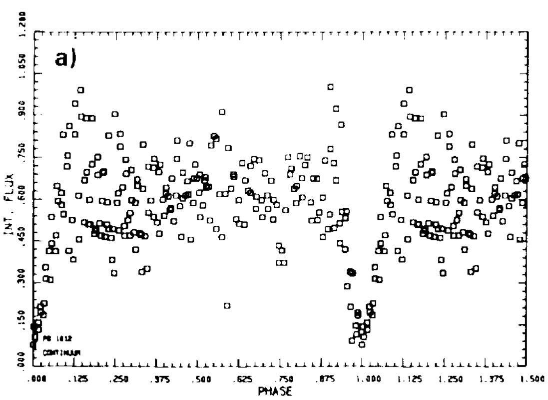
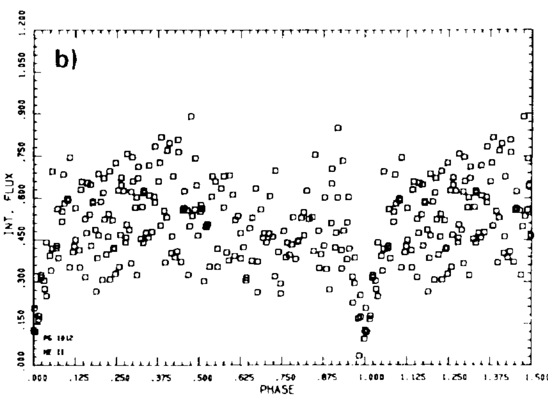


Figure 3-7. Spectral changes in RW Tri: a: changes during eclipse (Williams and Ferguson, 1982); b: long-term changes; the spectrum was taken at a different time than that displayed in Figure 3-7a (Williams, 1983).





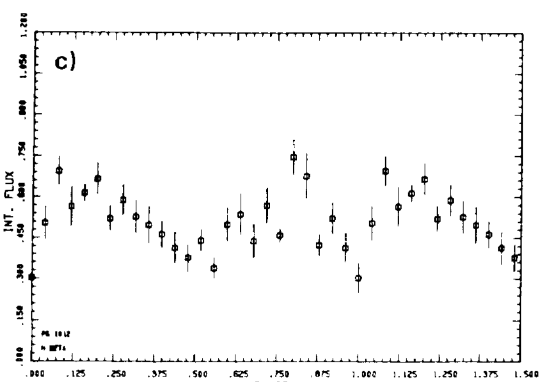
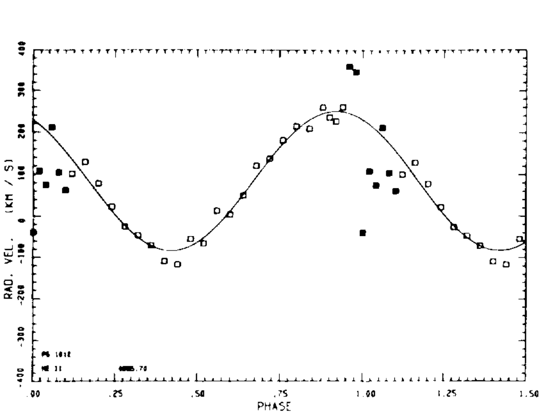
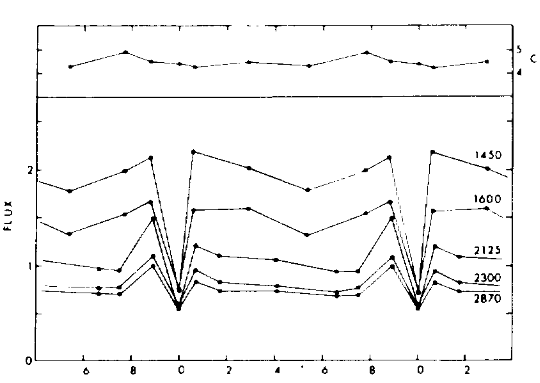


Figure 3-8. (above and left) Orbital light curves of RW Tri: a: continuum flux; b: He II 4686 Å emission line; c: Hβ emission (Honeycutt et al, 1986).

Figure 3-9. (below, left) Rotational disturbance in the radial velocity curve of He II of SW Sex during optical eclipse (Honeycutt et al, 1986).

Figure 3-10. (below) UV eclipse light curves of UX UMa (Holm et al, 1982).





curve is a rough image of the continuum light curve, but the duration of the primary eclipse is decidedly shorter and less deep (in the case of SW Sex, for instance, 0.06 orbits for He II, compared to 0.08 for the continuum). Both Hβ and He I in SW Sex show a secondary eclipse which is not visible in the continuous light curve; in RW Tri there also is some indication for a secondary eclipse. Outside eclipse the line profiles do change around the orbit, but it is not clear whether these changes are related to the aspect the observer has of the system or to what extent the light source is intrinsically variable (e.g., Wargau et al, 1984).

In UX UMa and RW Tri Hβ and Hγ exhibit a double-peaked structure, with the radial velocity of the red and the blue components having the normal sine shape and the period of the orbital motion (Kaitchuk et al, 1983; Schlegel et al, 1983). In addition there is a third S-wave component moving between the two line peaks, with the same period but with a phase shift of 150° in UX UMa and of 180° in RW Tri — as is seen in dwarf novae. In SW Sex, and to a lesser degree in RW Tri, the radial velocity curves of He II 4686 Å and of C III — N III 4645 Å, but not of Hβ, show a clear rotational disturbance at primary eclipse (Figure 3-9).

Extensive studies of the UV radiation have been carried out by Holm et al (1982), and King et al (1983), on UX UMa, and by Sion (1985) on IX Vel. In UX UMa, the continuous radiation was found to be strongly eclipsed at the time of primary optical eclipse (Figure 3-10). The eclipse is the deeper the shorter the wavelengths. The presence of the hump prior to and also somewhat after eclipse is clearly visible at longer UV wavelengths, but it is not entirely absent at short wavelengths where it even seems to last for an entire orbital cycle (in dwarf novae the hump shows up in the UV very infrequently, and then only weakly). As to the strong UV lines, N V, Si IV, and He II are clearly eclipsed, whereas C IV is not eclipsed (King et al, 1983).

GENERAL INTERPRETATION: Photometrically and spectroscopically UX Ursae Majoris stars exhibit all characteristics of dwarf novae, with the single exception of outburst activity. Thus the understanding is that these stars can be regarded as dwarf novae with an essentially constant (high) mass transfer rate through the accretion disc.

OBSERVATIONAL CONSTRAINTS TO MODELS:

- *Dwarf novae, UX Ursae Majoris stars, and anti-dwarf novae share most of their characteristics except for their outburst behavior.* *(See 229)*
- *In some objects, optical color changes during eclipse are the reverse of what is seen in dwarf novae.*
- *Also unlike the case of dwarf novae, the hump in some objects is strong in UV wavelengths.*
- *Unlike in dwarf novae, hump maximum can occur before as well as after eclipse.*

III. ANTI-DWARF NOVAE

III.A. PHOTOMETRIC OBSERVATIONS

III.A.1. LONG-TERM VARIATIONS

ABSTRACT: The normal photometric appearance of anti-dwarf novae is indistinguishable from that of UX Ursae Majoris stars. Occasional drops in brightness by several magnitudes occur. During these times the objects resemble quiescent dwarf novae.

other nova-like stars: 113, 125

dwarf novae: 21

interpretation: 172

Stars which are classified as *anti-dwarf novae* or *VY Sculptoris stars* (just two names for the same thing) cannot be distinguished from the UX Ursae Majoris stars most of the time: they show orbital light curves like those expected for cataclysmic variables; the spectra consist of H emission lines, which may or may not be superimposed on broad shallow absorp-

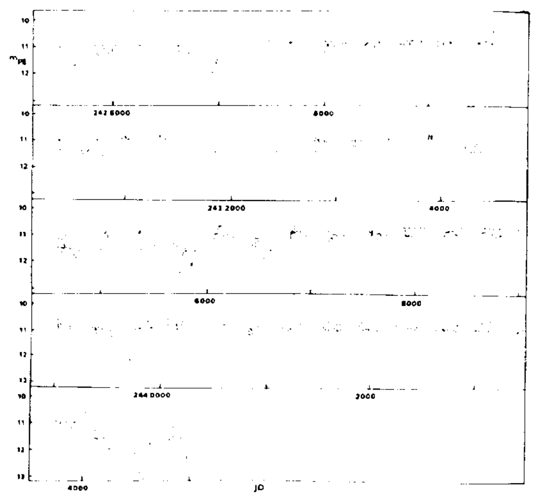


Figure 3-11. *Long-term variations of TT Ari (Hudec et al, 1984).*

tion features; and the brightness fluctuates about some mean value, deviating up and down irregularly by no more than about 1 magnitude. From time to time, however, the general brightness drops by a very considerable amount (some 2 - 3 mag, but see below) for as much as a few hundred days, after which the star again returns to the high level. Times for both decline and rise seem to be on the order of 100 days (Figure 3-11 — see also, e.g., Liller, 1980). In some objects the upper and the lower states have reasonably well defined brightness levels to which the star returns; in others there is no evidence for this. In contrast to dwarf novae, the high state for anti-dwarf novae is the normal state of the star. No periodicities comparable to outburst periods in dwarf novae could be found in anti-dwarf novae, as the drop in brightness occurs at random and unpredictably. In the best studied case, TT Ari, a couple of such drops often follow each other, after which the brightness remains essentially constant at high level for several years. No secular brightness changes could be detected for any star. Some objects (TT Ari, MV Lyr, and possibly others as well, except most anti-dwarf novae have not been adequately studied over longer times) drop to an unusually faint state at times, another 2 mag below the "normal" low (= intermediate) state.

III.A.2. CHANGES ON ORBITAL TIME-SCALES IN THE HIGH AND LOW STATES

ABSTRACT: The photometric appearance of an object can vary considerably from night to night. In TT Ari during the high state the hump is very pronounced in the UV. During high state this system also occasionally exhibits quasi-periodic oscillations, which never were seen during low state.

other nova-like stars: 96, 113, 114, 117, 119, 122, 125, 140

dwarf novae: 35, 46

interpretation: 177, 194

The orbital light curves of anti-dwarf novae during high state look like light curves of UX Ursae Majoris stars: for instance the light curve of MV Lyr is characterized by strong flickering up to 0.3 mag in which, however, no variability with the orbital period, like a hump, can be detected. TT Ari possesses a very pronounced hump in the light curve, on which flickering is superimposed (Figure 3-12a); and LX Ser and VZ Scl have eclipse light curves, which look very similar to those of UX Ursae Majoris stars, and also suffer appreciable flickering which mostly disappears during eclipse. A hump is visible in VZ Scl which can either precede or follow the eclipse (as is the case in some UX Ursae Majoris stars) (Warner and Thackeray, 1975; Horne, 1980). LX Ser usually does not possess a hump, though at some times it can be present. In the IR a secondary eclipse at about phase 0.5 is visible in VZ Scl (Sherrington et al, 1984). For LX Ser in the high state, there exist optical color measurements during an eclipse which look just like those in quiescent dwarf novae (Figure 3-13, compare with Figures 2-32, 2-33).

Photometric observations have been carried out for TT Ari during the intermediate state (V $\approx$ 14 mag; V $\approx$ 10.2 Mag at high state) and during the very low state (V $\approx$ 16.5 mag). The

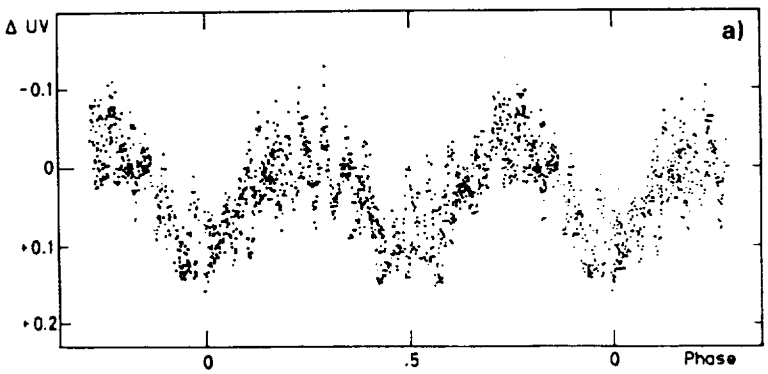
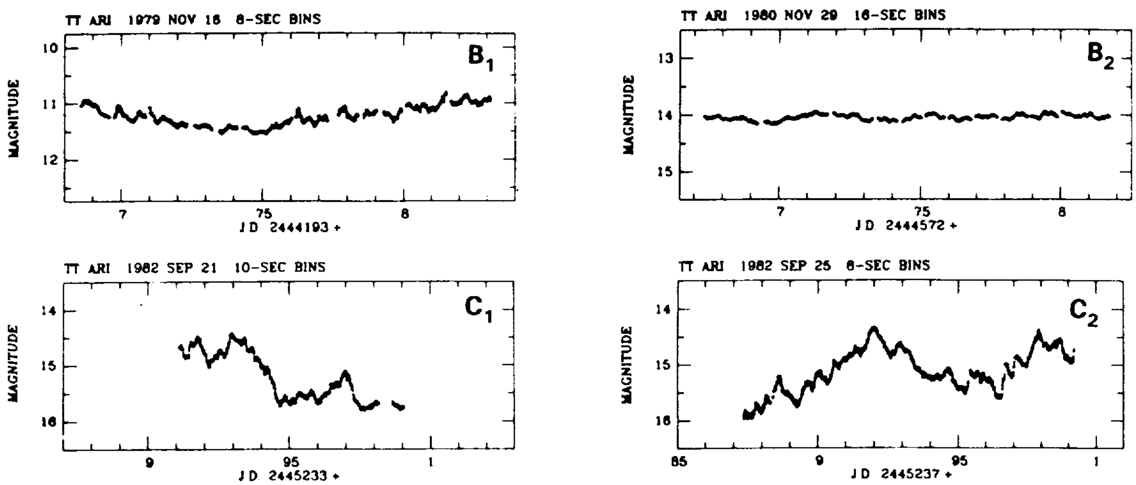


Figure 3-12. Orbital light curves of TT Ari: a: during high state (Smak, and Stepien, 1968); b: during intermediate level (Shafter et al, 1985); c: during low level (Shafter et al, 1985).



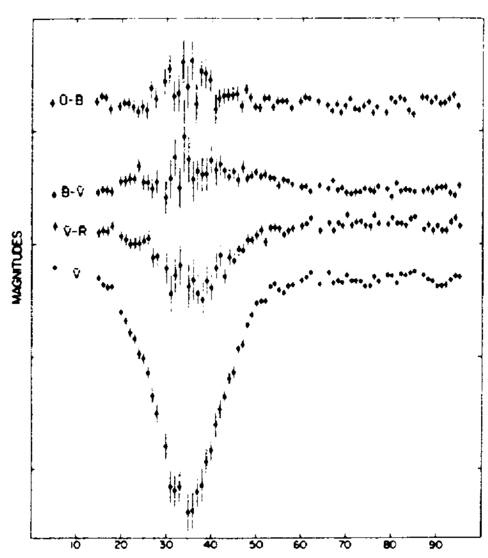


Figure 3-13. Color changes in LX Ser during eclipse (Horne, 1980).

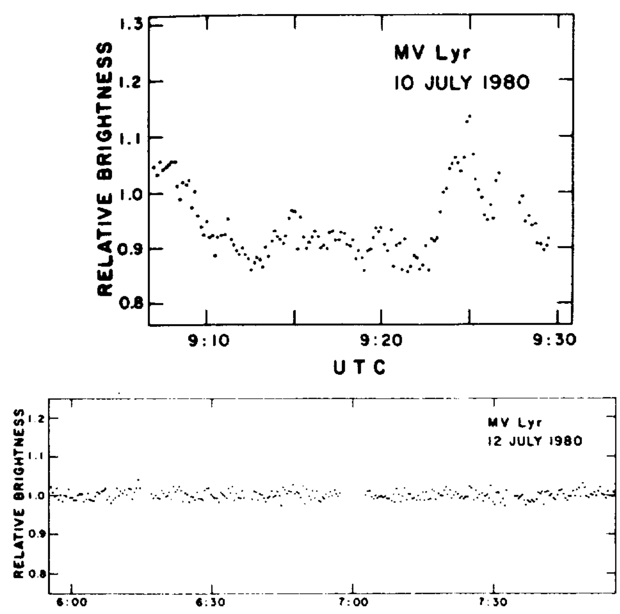


Figure 3-14. Optical light curves of MV Lyr in the low state, taken two days apart (Robinson et al, 1981).

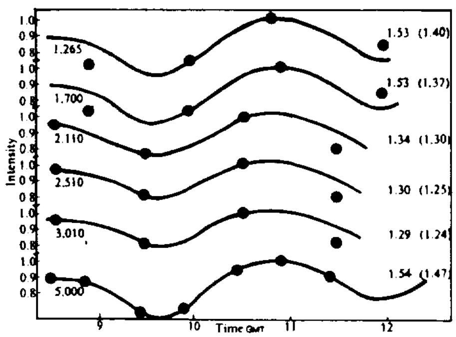


Figure 3-15. Wavelength dependence of the UV hump light curve of TT Ari in the high state (Jameson et al, 1982b), on the left the effective wavelengths for the light curves are indicated, since in this figure all amplitudes are normalized, on the right their actual amplitudes are given.

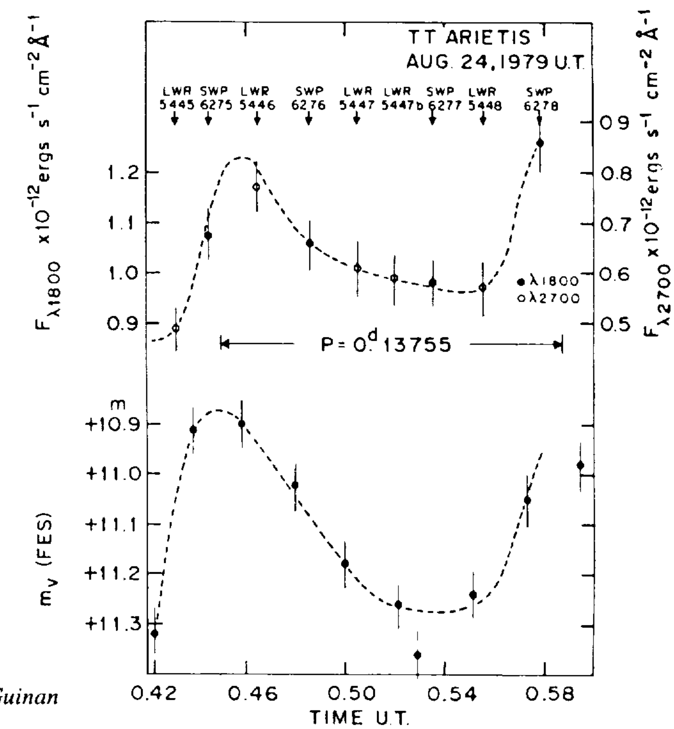


Figure 3-16. (right) UV light curve of TT Ari (Guinan and Sion, 1981).

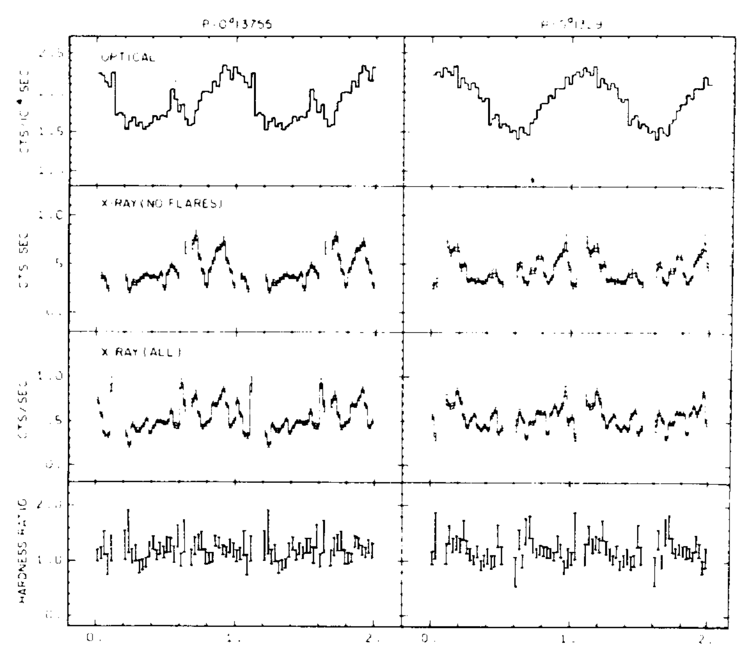


Figure 3-17. (left) X-ray photometry of TT Ari (Jensen et al, 1983).

hump and most of the flickering activity disappeared at intermediate state, leaving an essentially constant light curve (Figure 3-12b). In the very low state the flickering is present again (Figure 3-12c), and its absolute intensity is fainter than at higher state; whether or not an orbital hump is present cannot be decided from the data available, but clearly the light curve is not as smooth and straight as during the intermediate brightness. Measurements of MV

Lyr during faint state show strong activity during one night (Figure 3-14a); two nights later, no photometric changes in excess of slight random variations can be detected at the same optical brightness (Figure 3-14b).

TT Ari has been observed photometrically at IR wavelengths during the high state (Jameson et al, 1982b). The light curve is highly variable on times-scales of hours, though no relation to orbital variations is evident; simultaneous light curves in the optical and at different IR wavebands are only vaguely similar and strongly change from one night to the next.

At UV wavelengths, brightness changes in connection with the orbital motion can clearly be seen. In TT Ari the hump amplitude is seen to decrease between 5000 and 3000 Å, but then increases again with decreasing wavelength, to be at least as pronounced at 1500 Å as in the optical (Figure 3-15), much unlike in dwarf novae, in which the hump amplitude strongly decreases with decreasing wavelength and is only marginally (if at all) detectable in the UV. From phase-resolved spectroscopy, a UV light curve has been derived for TT Ari in the high state (Figure 3-16) which, like the optical light curve, clearly reflects the orbital motion of the system.

TT Ari has been observed with the EINSTEIN satellite in X-rays and simultaneously in the optical (Jensen et al, 1983b). The X-ray flux is strongly variable on most time-scales. There is some evidence for orbital variation in the X-rays, mostly in that the X-ray flickering amplitude increases around times of the optical hump (Figures 3-17). The hardness ratio, i.e., the color of the X-ray radiation, remains unchanged during the orbital cycle.

Polarization of the radiation from TT Ari and KR Aur of some 0.3% has been measured (Popova and Vitrichenko, 1979; Szkody et al, 1982a), in full agreement with observations of dwarf novae.

III.A.3. FLICKERING AND OSCILLATIONS

ABSTRACT: Just as in dwarf novae, flickering is also observed in anti-dwarf novae at high as well as low states. Only during the high state in some objects oscillations occasionally can be seen.

other nova-like objects: 98, 113, 117, 121, 122, 128, 141

dwarf novae: 54, 56

interpretation: 151, 181, 185, 213

In all systems, rapid flickering is observed with amplitudes of some hundredths to some tenths of a magnitude on time-scales of seconds to minutes. It is usually strongly diminished in amplitude or disappears altogether during eclipses in the high state. No other relation with the orbital phase than this could be detected. Simultaneous X-ray and optical observations of TT Ari during the bright state revealed a strong relation between flickering observed in both wavelength ranges: The power spectra look very similar, the flickering in X-rays is delayed by some 58 seconds with respect to flickering in the optical (Jensen et al, 1983). The flickering amplitude amounts to some 15% to 20% in the optical and to some 70% to 100% of the flux in the X-rays. High-speed photometric observations of TT Ari and MV Lyr in different brightness stages showed that flickering can also be present in low states. Two observations of MV Lyr at low state were obtained two days apart (Robinson et al, 1981): very pronounced flickering similar to that seen during the bright state was present during one observing run, while brightness fluctuations did not exceed photon noise during the next run; the overall optical brightness had not changed during this time. In similar observations of TT Ari, no flickering could be seen at an intermediate brightness level, whereas it was even more conspicuous at low state than during high state; the absolute amplitude was somewhat lower at low state (Figure 3-12). In none of these observations could a relation with orbital phases be detected. Flickering in the IR is about as strong as in the optical (Jameson et al, 1982b).

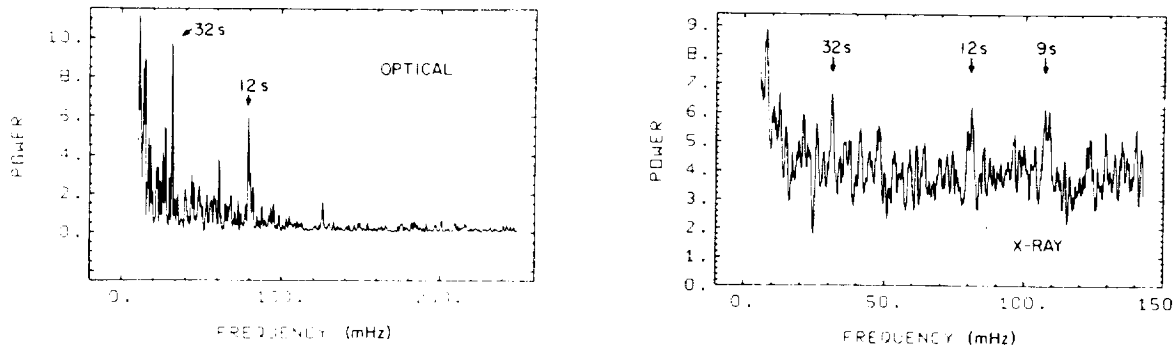


Figure 3-18. Optical and X-ray power spectra of TT Ari from simultaneous observations (Jensen et al, 1983).

Besides the flickering, there is occasionally also a component of quasi-periodic oscillations with periods on the order of seconds or minutes during high states. No detection during low states has ever been reported. The most extensive investigations have been carried out for TT Ari (Mardirossian et al, 1980; Jensen et al, 1983). The oscillations here are not always present. Periods vary erratically between 32 and 43 sec. In the power spectra which were extended over a lengthy run the peaks of the oscillation frequencies are not strictly monochromatic, but rather have a narrow bandwidth which is again variable from one run to another. It is not clear whether the oscillations in TT Ari are intrinsically polychromatic (which would distinguish it from other cataclysmic variables in which the peaks are either monochromatic or much broader than those in TT Ari), or whether this is merely due to the coarse time resolution. Periods and life times are on roughly the same order as in other cataclysmic variables.

Simultaneous optical and X-ray observations of TT Ari have revealed oscillations at different frequencies. A monochromatic 32 sec oscillation and a non-monochromatic oscillation around 12 sec were seen in both energy regimes; in addition, a narrow frequency band was present around 9 sec only in X-rays (Mitrofanov, 1980; Jensen et al, 1983; Figure 3-18). The pulsed fractions are 15 - 25% in the X-rays, and some 1.5% in the optical — in close analogy to observations of dwarf novae. No time relation between optical and X-ray oscillations has been reported, but the identical frequencies at both wavelengths lead one to suspect a physical connection between the observed phenomena.

III.B. SPECTROSCOPIC OBSERVATIONS

ABSTRACT: During the high state the spectra exhibit characteristics of outbursting dwarf novae, during low state those of quiescent dwarf novae. Contrary to dwarf novae, in which the UV is more affected by the outburst activity, in anti-dwarf novae the optical changes most. The spectrum of MV Lyr is highly variable during high state. The spectroscopic period of TT Ari is distinctly different from the photometric.

other nova-like stars: 99, 116, 119, 122, 124, 134, 141

dwarf novae: 45, 65, 80

interpretation: 151, 192

The general flux distribution of anti-dwarf novae during the high state is not any different from that of other cataclysmic variables. During the high state, characteristics of outbursting dwarf novae can be seen. In some of the anti-dwarf nova systems, variations of the line profiles with orbital phase have been observed. The two systems LX Ser and VZ Scl show changes in their spectra during eclipses which affect the

c-3.

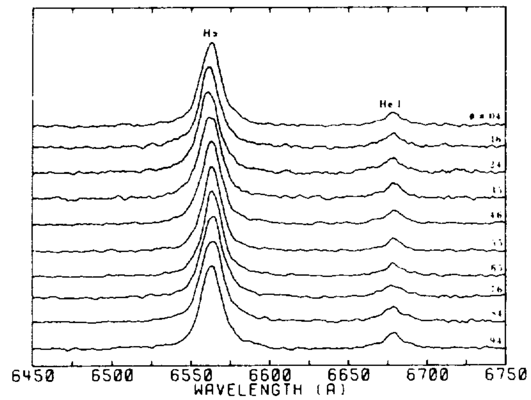


Figure 3-19. Phase-resolved spectroscopy of KR Aur during the high state (Shafter, 1983).

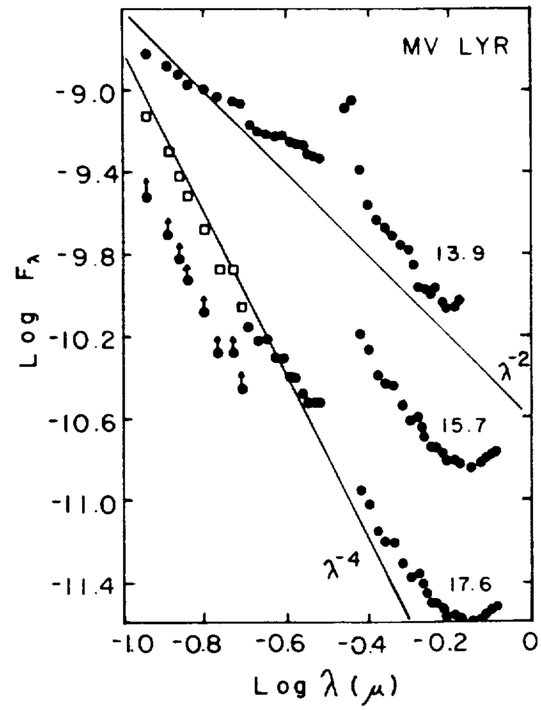
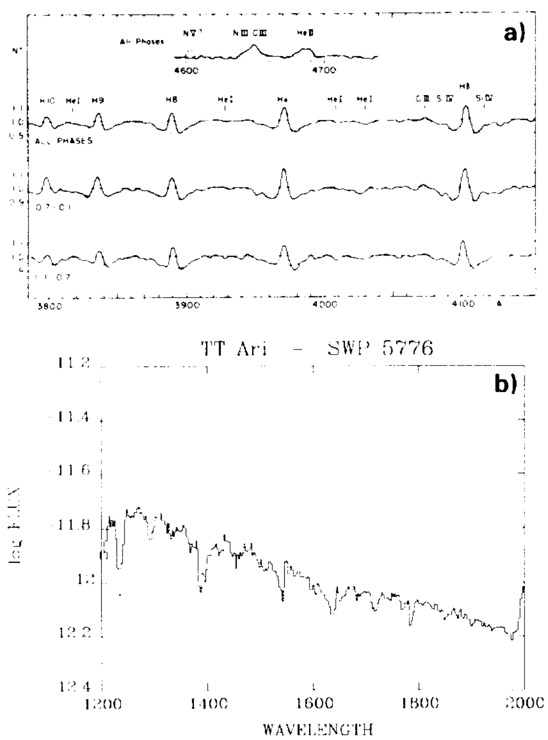


Figure 3-20. Flux distribution of MV Lyr during high, intermediate, and low states (Szkody and Downes, 1982).



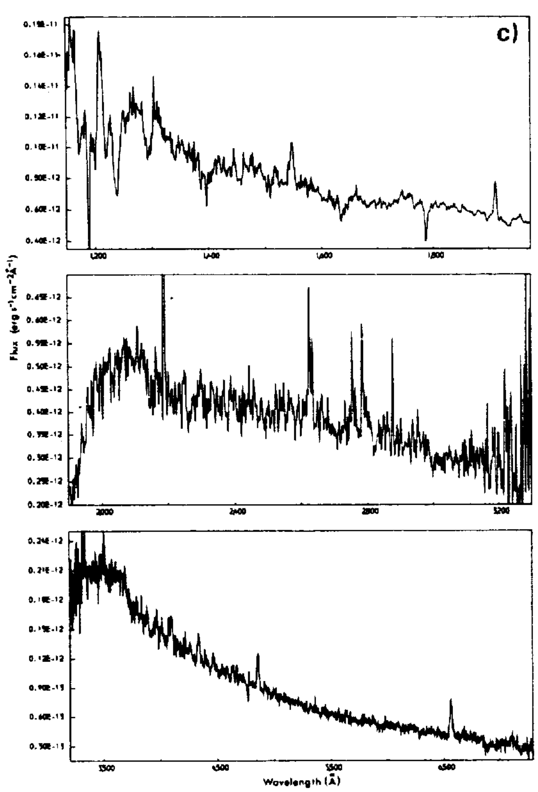


Figure 3-21. Spectral appearance of TT Ari: a: optical spectrum in the high state (Cowley et al, 1975); b: UV spectrum in the high state; c: optical and UV spectra in the high state between two successive low states (Jameson et al, 1982b); d: optical spectra at (a) high state and (b) intermediate brightness (Voikhanskaya, 1983b); e: UV spectrum at intermediate brightness (Krautter et al, 1981b); f: Optical spectrum at low brightness level (Shafter et al, 1985); g: UV spectrum at low brightness level (Shafter et al, 1985).

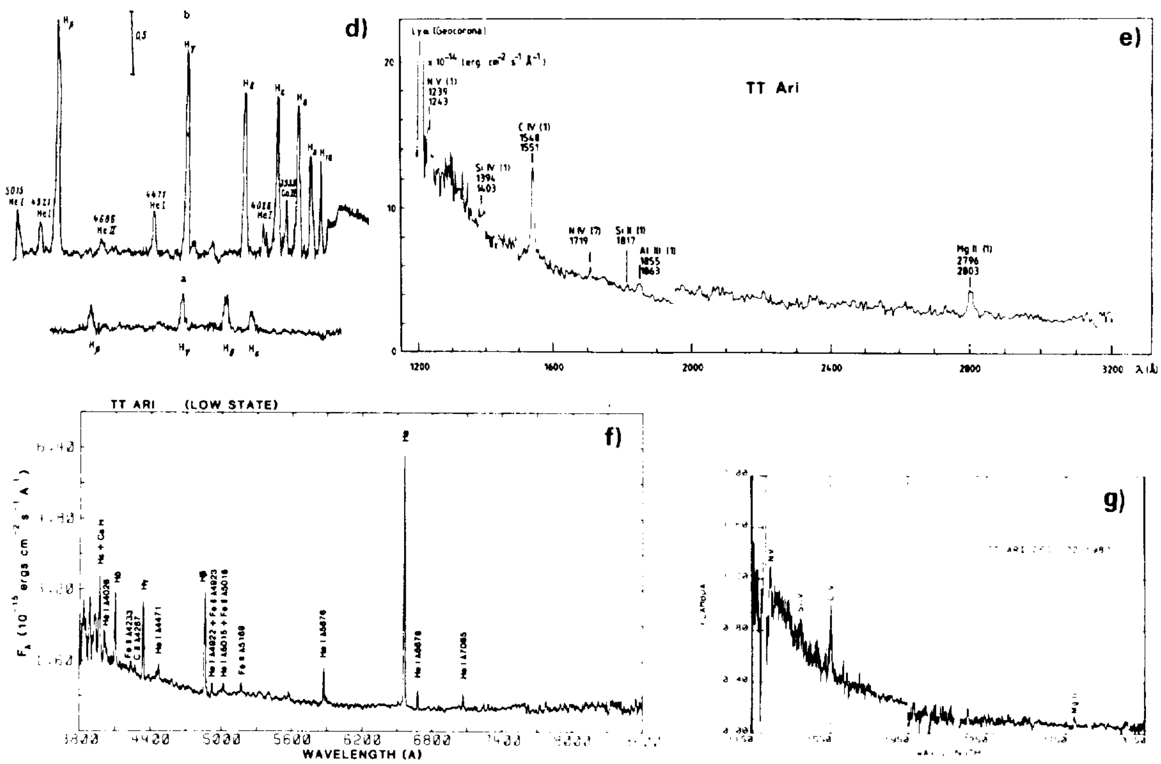
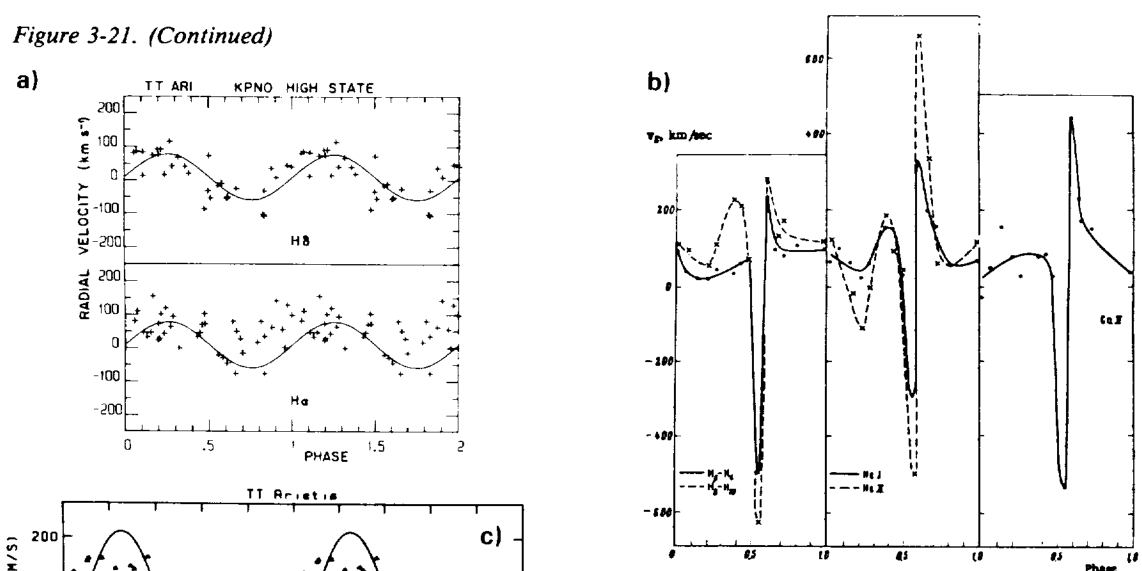


Figure 3-21. (Continued)



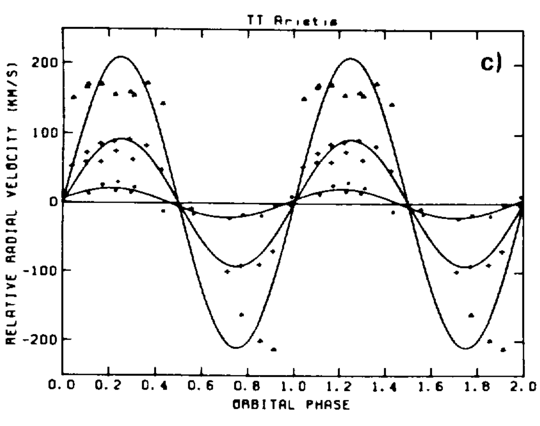


Figure 3-22. Radial velocity curves of TT Ari: a: Hα and Hβ curves during high state (Thorstensen et al, 1985 — the least square sinusoidal fit to Hδ is plotted in both panels); b: at intermediate state (Voikhanskaya, 1983b — the solid and dashed lines are fits to observations of different lines as indicated in the figures); c: at low state, measured from different parts of the line profiles (peak component: dots; broad base: crosses; narrow base: triangles).

continuum shape as well as the strengths and profiles of the lines, much like UX Ursae Majoris systems. S-wave variations in the H emission profiles are seen in LX Ser, TT Ari, and KR Aur, although in no system, not even in the eclipsing* system LX Ser, are the lines double-peaked (Young et al, 1981a; Shafter, 1983; Shafter et al, 1985; and Figure 3-19). In the lower states, spectroscopically, the systems resemble more quiescent dwarf novae. Changes in the continuous flux distribution between high and low state, however, are of a different quality than in dwarf novae: while in dwarf novae most of the flux changes during an outburst cycle occur at UV wavelengths, in anti-dwarf novae it is the optical which is more strongly affected, although clearly the changes occur at all wavelengths. Changes in the overall distribution between high, intermediate, and low state in MV Lyr are shown in Figure 3-20 (compare with, e.g., Figure 2-76): the drop in brightness affects more the optical wavelengths than the UV. During the low state in MV Lyr, as well as TT Ari, the secondary component becomes prominent at low energies (Chiapetti et al, 1982; Shafter et al, 1985).

The different brightness stages not only show effects on the continuum shape, but even more conspicuous effects in the line spectra. Changes in the two best-studied systems, TT Ari and MV Lyr, are described in the following. During the high state, before the first recorded spectacular low state in fall 1980, the spectrum of TT Ari exhibited moderately strong H emission lines in the optical, which were placed in wide shallow absorptions — strongly reminiscent of a dwarf nova during decline from outburst (Figure 3-21a). The UV was dominated by the usual strong resonance lines in absorption, with C IV exhibiting a P Cygni profile (Figure 3-21b). Between the two minimum states in fall 1980 ($m_v \approx 14.5$), and fall 1982 ($m_v \approx 16.5$), there was a time when TT Ari returned to its normal brightness around 12.0 mag. In spectra taken during this period, no pronounced absorption shells around the H emissions are visible. In the UV, C IV and Mg II were entirely in emission, and the other resonance lines were in absorption (Figure 3-21c).

During the intermediate state at $m_v \approx 14.5$, the UV lines all went into emission, and the continuum was bluer than in the bright state; the optical lines became narrower and much stronger in emission, correspondingly the Balmer jump was seen strongly in emission (Figures 3-21d, 3-21e). Comparing the flux at intermediate and low (≈ 16.5 mag) states, there is hardly any change in the UV shortward of 1500 Å; at 3000 Å, however, the flux decreased by a factor of 5, and in the optical by a factor of nearly 100, by which, in total, the spectrum has steepened considerably toward shorter wavelengths. In line radiation in the UV no major changes can be seen; the optical lines become even much narrower than during intermediate state, with the H lines, as at high state, again placed in absorption shells (Figure 3-21f).

MV Lyr exhibits a highly variable line spectrum during its bright state. MacRae (1952) reports the star to show weak H lines and strong He II 4686 Å (it is not clear from his description whether these lines are in absorption or in emission) at a brightness of 12.18 mag. Diffuse shallow absorptions were also seen in 1952; in 1954 MV Lyr exhibited strong H emissions; and in 1963 narrow emission lines and rapid radial velocity variations were reported (Voikhanskaya, 1980). All this seems to have happened at roughly the same optical brightness. In 1977 through early 1979 Voikhanskaya observed MV Lyr several times spectroscopically; all throughout this time the AAVSO reports the apparent magnitude to fluctuate around 12.5 mag. In July 1977, a plain continuum without any appreciable lines was observed, which persisted for at least 8 months. In summer 1978, H emission lines were seen which briefly dis-

*Normally eclipsing systems show double-peaked lines.

appeared shortly afterwards around mid-July; they reappeared and stayed until late October when they gradually vanished and left only a continuous spectrum. This then seems to have lasted at least until mid-January 1979. When emissions were present, the line profiles of Hβ, Hγ, and Hδ were subjected to extremely rapid variations in strength and position on time-scales of minutes, while Hα stayed roughly constant. And over longer time-scales of weeks, as it seems, the strength of all these lines, including Hα, changed considerably but differently for different members of the Balmer series. Continuous spectra at times exhibited wide shallow absorption shells of H with some weak emission cores. No He could be detected.

All published spectra of fainter brightness states of MV Lyr show strong emission lines of mostly H and He which become the narrower the lower is the overall brightness level (Robinson et al, 1981; Schneider et al, 1981; Szkody and Downes, 1982); and the lower the level is, the flatter (cooler) become the optical flux distribution, much like the spectra of TT Ari. Whether or not spectra at fainter states are generally more stable in appearance than at high state is not known. Some variability is clearly present: in spectra of the very faint state absorption shells can be seen at times around the H emission lines which are not visible at other times when the system has roughly the same optical brightness (Schneider et al, 1981; Szkody and Downes, 1982). MV Lyr has been observed on two occasions at $m_v \approx 17.3$ mag and 16.5 mag, when the continuum slopes were almost identical but the line strengths were very different (Robinson et al, 1981).

In TT Ari the spectroscopic period, as determined from the radial velocity, is clearly different from the photometric period, as determined from the repeating hump. Furthermore, when all radial velocity data from different epochs and brightness stages are taken together, no period can be found which fits all the data. If, however, observations from high, intermediate, and low states are analyzed separately, they all lead to a spectroscopic period of $0.^{d}1375511$, implying phase shifts of the radial velocity of 0.28 and 0.58 orbital periods, respectively, between the high and low states (Shafter et al, 1985; Thorstensen et al, 1985). The photometric period was found to decrease from $0.^{d}1329$ in 1961/2, to $0.^{d}1327$ in 1966, and to $0.^{d}1324$ in 1978 (Thorstensen et al, 1985). It is not clear what these findings mean in terms of a physical model of TT Ari; it only is clear that more than just orbital rotation causes the observed changes. A case of similar confusion seems to be the dwarf nova CN Ori, for which several photometric periods have been determined from various observations which may or may not be identical with the spectroscopic period (see Chapter 2.II.B.3).

For TT Ari radial velocities have been obtained at all brightness stages (Figure 3-22). In the high state, the radial velocity curve of Hα can be seen to be considerably more distorted than that of Hδ; furthermore, the γ-velocity is systematically lower for higher-order Balmer lines. At intermediate brightness, the radial velocity curve is highly distorted and asymmetric with a sharp short-lasting drop in the velocity at about phase 0.5 of the spectroscopic period, while the equivalent width of the line stays constant. This is probably not a rotational disturbance since, first, TT Ari is not known to have an eclipse; second, if the change in radial velocity were caused by eclipse effects, one would expect to see first a rise in the radial velocity followed by a drop, and not vice versa, unless the white dwarf in TT Ari would be rotating retrogradely; and third, the disturbation lasts far too long to be related to the white dwarf. At the very low state, the curve determined from the broad base of the lines again has a more sinusoidal shape and is in fairly good agreement with the radial velocity determined from the high state (as is also the case in many other cataclysmic variables, for which different radial velocities are determined from different parts of the line profile; this effect is very pronounced in TT Ari during the low state).

GENERAL INTERPRETATION: Like the UX Ursae Majoris stars, anti-dwarf novae can be distinguished neither spectroscopically nor photometrically from dwarf novae (at some activity stage), except for their outburst behavior. Thus anti-dwarf novae are also considered to be essentially identical to dwarf novae in their physical nature. The mass transfer rate is assumed to be fairly high and stable for most of the time; only at (unpredictable) times is it considerably reduced.

OBSERVATIONAL CONSTRAINTS TO MODELS:

- *Dwarf novae, UX Ursae Majoris stars, and anti-dwarf novae share most of their characteristics except for their outburst behavior.*
- *Unlike in dwarf novae, the changes between high and low state in anti-dwarf novae have a considerable effect on the flux at long wavelengths.*
- *Optical color changes during eclipse in some anti-dwarf novae are the reverse of what is seen in dwarf novae.*
- *Also unlike in dwarf novae, the hump is strong at UV wavelengths in some anti-dwarf novae.*

IV. DQ HERCULIS STARS

Observationally the criterion for a cataclysmic variable to be classified as a *DQ Herculis star (intermediate polar)** is the existence of more than one photometric period, one of which is identical with the spectroscopic period (and this is the orbital period), and at least one other which is appreciably different from this. In addition, all these periods must be strongly coherent over all times the system has been observed.

This definition is vague enough to actually render the class of DQ Herculis stars highly inhomogeneous, comprising objects which are also classified as members of, or bear strong similarities to, other sub-classes of cataclysmic variables (incidentally, the prototype DQ Her is an old nova; see Chapters 6 and 8). Two main groups within this class can be distinguished.

The first group consists of stars with one additional photometric period which is some two orders of magnitude smaller than the orbital period (the systems DQ Her and AE Aqr belong to this group; for several years also V533 Her had to be regarded as one); originally only these stars were called "DQ Herculis stars."

The second group consists of stars with additional photometric periods that are only about one order of magnitude smaller than the photometric period (like TV Col, FO Aqr, V1223 Sgr, BG CMi, and EX Hya, although the latter system is different from all the others); for most of these objects two or more, usually fairly similar, additional periods have been detected in the optical, one of which often also shows up strongly in the X-rays. Originally these objects were referred to as "intermediate polars," because their additional periods are intermediate between the very short periods of the DQ Herculis stars (which are understood to be the rotational periods of the white dwarfs, see Chapter 4.III.F.2) and the synchronous rotation of the polars (Chapter 3.V).

Then there is one additional group of "related objects:" their photometric period is different from the spectroscopic period, but other than "real" DQ Herculis stars they do not have one photometric period which is identical with the spectroscopic period, e.g., the systems HR Del, V603 Aql, TT Ari, are regarded as "related" (see Ritter, 1987). These will not be regarded here, but rather these objects have been dealt with in the context of the other sub-classes of cataclysmic variables (see index).

The classification of the systems AE Aqr and WZ Sge is controversial: both are at times referred to as peculiar dwarf novae or, alter-

*There is no general agreement as to how these terms shall be used: some authors use them as equivalents, others distinguish between them according to the definitions given below.

natively, as some kind of nova-like stars. Since the detection of superhumps during the last outburst of WZ Sge, this object is usually classified now as a dwarf nova of sub-type SU Ursae Majoris, and has been dealt with as such in Chapter 2, although the 28 sec pulsation also would justify a classification as a DQ Herculis star. As for AE Aqr, one striking feature is a highly stable pulsation with a period of some 33 sec, while its dwarf nova activity is restricted to mere irregular fluctuations; it will be dealt with in this section on DQ Herculis stars.

Concerning their general appearance and behavior, DQ Herculis stars exhibit all characteristics common to cataclysmic variables, including even nova outbursts in some cases. However, they are fairly individualistic as single objects, and except for the photometric periods they do not have much in common concerning details.

Polarization in the emitted radiation is undetectable or just barely present.

IV.A. LONG-TERM VARIATIONS AND GENERAL ORBITAL CHANGES

ABSTRACT: The long-term behavior of all members of this class, when considered together, comprises the full range of possibilities found in cataclysmic variables from nova outbursts to dwarf novae and nova-like activity. Respective variations are found in orbital photometric variability.

other nova-like stars: 102, 125

dwarf novae: 21

interpretation: 171

Long-term variabilities of DQ Herculis stars span the entire range of possibilities exhibited by cataclysmic variables. Two objects, DQ Her and V533 Her* are old novae. DQ Her had a 12.8 mag outburst in 1934, V533 Her had a 11.3 mag outburst in 1963; when these outbursts are compared to those of other novae, there seems to have been nothing unusual about them (Chapters 6 and 8). EX Hya more resembles dwarf novae in its outburst activity. Normally it fluctuates about a brightness of 13 mag with occasional flares of some 0.5 to 1.0 mag amplitude; in intervals of 450 to 500 days it has dwarf nova-like eruptions of some 2 mag amplitude which only last for some 4 days (Córdova and Riegler, 1979). AE Aqr fluctuates irregularly between some 10 mag and 11 mag, without any detectable periodicity in this behavior (AAVSO Report 29). AO Psc fluctuates about 13.3 mag with amplitudes of some 0.4 mag (Patterson, 1985); inspection of some old photographic plates revealed only one excursion to a brightness well below normal (Belserene, 1981). TV Col, on the other hand, has remained close to 14 mag ever since detection, except for one occasion in November 1982, when it rose by some 2 mag for about 2 days. And finally for V1223 Sgr, which normally can be found near 12.3 mag, a total of five drops by 2 – 3 magnitudes have been reported (Belserene, 1981).

Light curves on orbital time scales are highly reminiscent of other cataclysmic variables: they may or may not show humps and eclipses, and suffer substantial flickering. Different from what normally can be found in cataclysmic variables, the coexistence of several photometric periodicities often gives the light curves a very irregular appearance. Since the systems are fairly different from each other photometrically, DQ Herculis stars and intermediate polars, in the stricter sense, will be dealt with separately.

* As will be seen, this object cannot really be regarded as a DQ Herculis star, but since it bears many features characteristic of DQ Herculis stars, it will be dealt with briefly in this chapter.

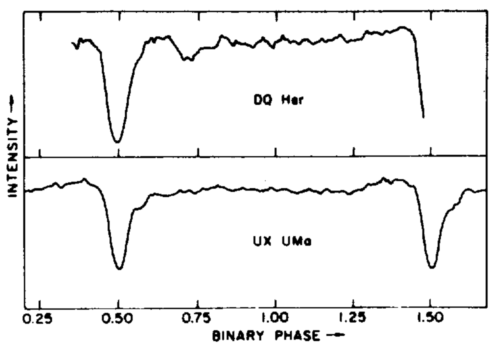


Figure 3-23. Orbital light curve of DQ Her, as compared to the light curve of UX UMa (Petterson, 1980).

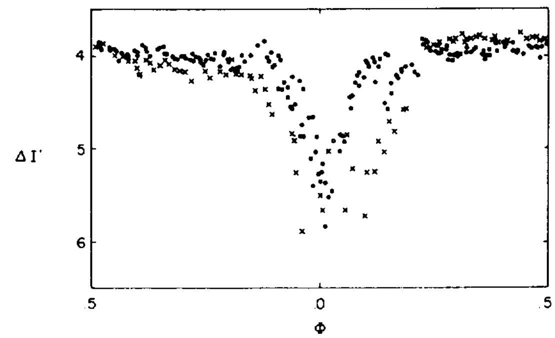


Figure 3-24. IR eclipses of DQ Her, measured at different times (Nelson and Olson, 1976).

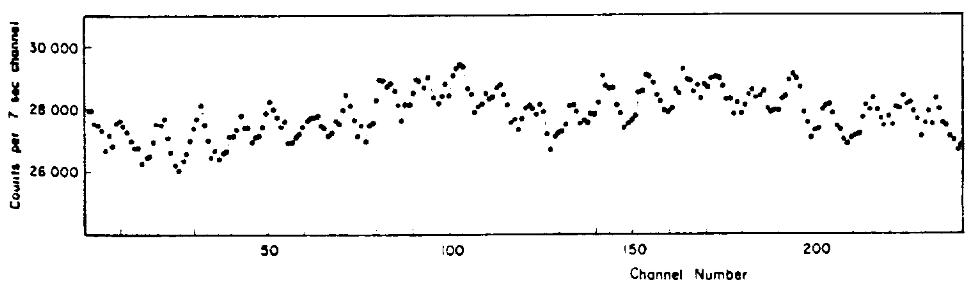


Figure 3-25. 71 sec oscillation in DQ Her (Warner et al, 1972).

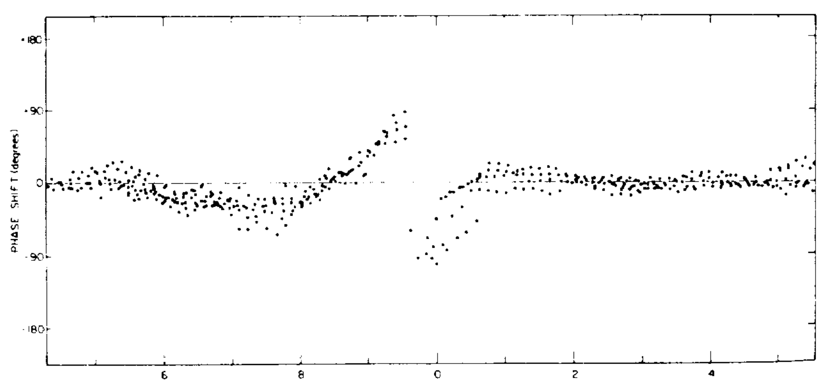


Figure 3-26. Phase shift of the oscillations in DQ Her during eclipse (Patterson et al, 1978b).

IV.B. DQ HERCULIS STARS (in the narrow sense)

IV.B.1. DQ HERCULIS

ABSTRACT: The orbital light curve of the prototype DQ Her is almost identical to that of UX UMa; the color dependence is somewhat different. A 71 sec pulsation has been seen in all photometric observations. The spectrum is in no ways exceptional for a nova-like star.

other nova-like stars: 96, 102, 117, 119, 122, 125, 140

dwarf novae: 35, 46, 65

interpretation: 190

The orbital light curve of DQ Her is almost identical to that of UX UMa (Figure 3-23), the orbital periods are different by only 4.4 minutes: there is a primary eclipse of about one magnitude depth, the exact shape and

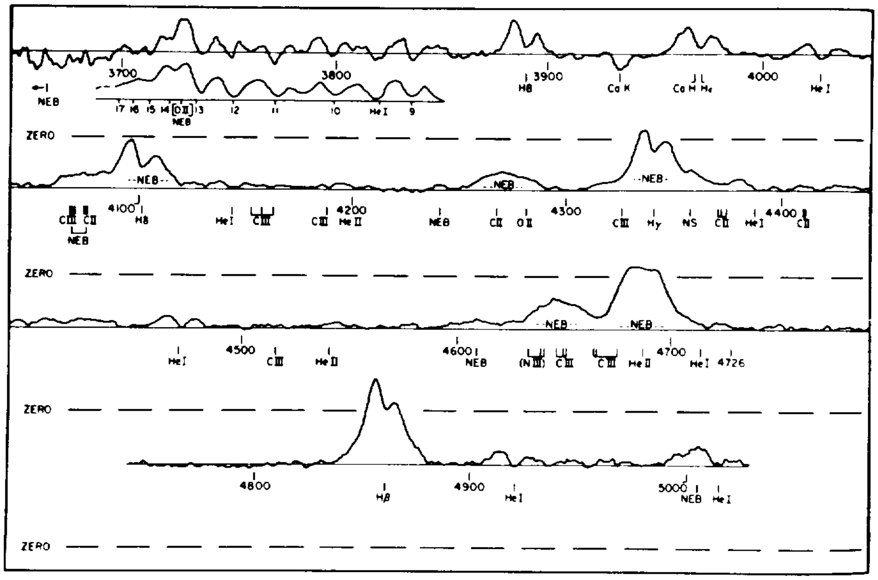


Figure 3-27. Optical spectrum of DQ Her (Hutchings et al, 1979).

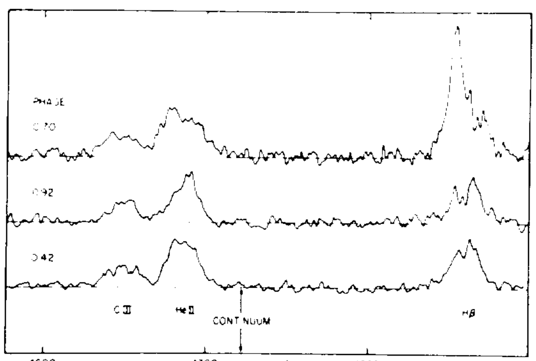


Figure 3-28. Optical spectrum of DQ Her through eclipse (Hutchings et al, 1979).

width of which are variable from cycle to cycle; the ingress is substantially more stable in appearance than the egress; the egress is asymmetric and most of the time, as in UX UMa, has a halt lasting for a couple of minutes shortly before reaching normal brightness; shortly after egress between phases 0.110 and 0.325 (with respect to central eclipse) there is a phase of extremely-large-amplitude irregular variability, the particular character of which again varies from cycle to cycle; after that, like in UX UMa, the light level decreases until about phase 0.7, when it starts rising again and a hump-like feature which will be interrupted by the eclipse becomes visible; the hump maximum can occur before as well as after the eclipse, and the amplitude varies strongly with time (e.g., Walker, 1957; 1958). Unlike in UX UMa, where the eclipse is deeper in U and V than in B, in DQ Her in 1978 it was observed to become deeper with decreasing wavelength, whereas in 1954 it became shallower (Walker, 1957; Schneider and Greenstein, 1979); this change in behavior probably can be ascribed to the influence of the surrounding nebulosity which had been ejected during the nova outburst. At IR wavelengths the effect is partially reversed: in I the depth of the eclipse is about the same as in U (Mumford, 1976). Furthermore, features are considerably more distorted in the IR eclipse than in the optical, and they are subject to even stronger temporal changes (Figure 3-24). No hump can be seen in the IR when it is clearly visible in the optical (Nelson and Olson, 1976); nor can a secondary eclipse be detected.

The times of eclipse, which are a pure effect of binary motion, show a sine-like modulation with a period of about 14 years; due to the relatively short time during which this star has been observed, it is not clear whether these changes are strictly periodic or merely cyclical (Patterson et al, 1978b).

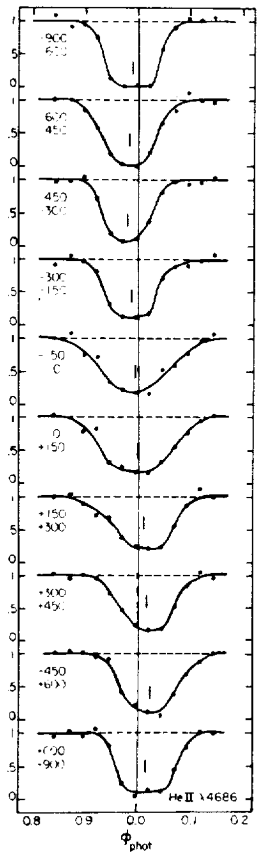


Figure 3-29. Eclipse profiles of He II 4686 Å as measured at various distances from the line center (Young and Schneider, 1980).

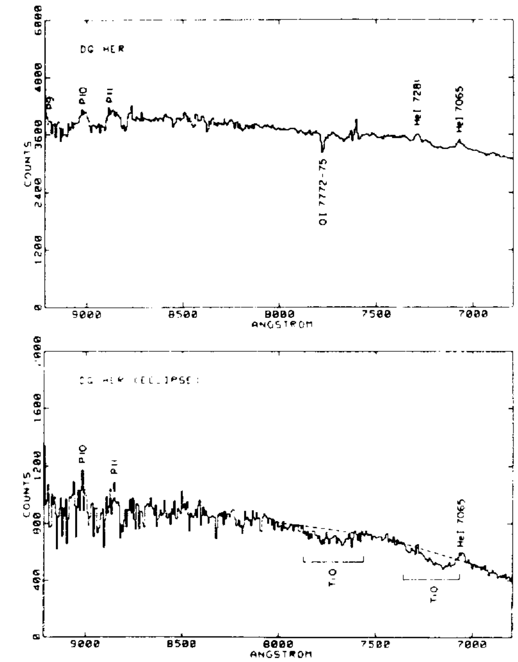


Figure 3-30. IR spectrum of DQ Her outside and during eclipse (Young and Schneider, 1981).

The strong, seemingly irregular brightness changes near phase 0.2 in DQ Her encouraged closer inspection, which eventually revealed a monochromatic periodicity of 71 sec. This can be found in all observations in the optical with sufficiently high time resolution up to wavelengths of at least 8600 Å (Figure 3-25) — superimposed is an irregular flickering with lower frequencies (Chanan and Nelson, 1979). The amplitude of this pulsation varies over the orbital cycle: it has an amplitude of 0.3 to 0.5 mag near phase 0.1, and gradually decreases until phase 0.6 when it is barely detectable; it increases again as the hump becomes visible; during eclipse it is again strongly diminished, is entirely absent for two short moments around mid-eclipse, and then recovers rapidly and is again most pronounced near phase 0.1 (Warner et al, 1972; Patterson et al, 1978). In addition, the pulsed fraction of the flux seems to vary over longer time-scales (Chanan and Nelson, 1979). Regarding pulse times during the orbital cycle with respect to the average ephemeris, a change of 360° in phase shortly before mid-eclipse can be seen (Figure 3-26). When all observations of the 71 sec pulsations since 1959 are regarded together, a secular decrease in the period becomes apparent (Patterson et al, 1978b).

No dependence of the pulse times on wavelengths could be detected, while the amplitude in U is almost 70% of that in V. Only the He II 4686 Å and C III — N III 4640 Å emission lines are much more strongly modulated than the underlying continuum. In addition, in He II, there is a phase shift in pulse arrival times with respect to the continuum pulsations, which increases over the width of the line with increasing wavelength: the line center pulsates in phase with the continuum, the blue wing lags behind, and the red wing leads it; the largest amplitude of the pulsation is shifted to wavelengths slightly longward of the line center (Chanan and Nelson, 1979).

In the optical spectrum of DQ Her, all lines except Ca II K are seen in emission (Figure 3-27). Carbon lines are unusually strong. There are large differences in profiles between H, He I, and He II and C lines: H, and He I, and, weakly, He II show double-peaked profiles, whereas all C lines are single peaked. There are pronounced profile changes over the orbital cycle, in particular during eclipse when all lines are considerably weakened (Figure 3-28). The eclipse shape is dependent on the wavelength in the line profile and is in general fairly asymmetric (Figure 3-29): the curve is roughly symmetric and centered about the continuum eclipse for the line center; it becomes asymmetric and the center is shifted away from the center of the continuum eclipse for higher Doppler velocities, and ingress and egress occur more rapidly at higher velocities; the total width of the eclipse is approximately 0.11 of the orbital cycle for all velocities except for the line center, where it increases to 0.15 of the total rotational period. The blue wings of the Balmer lines are eclipsed before the respective parts of He II 4686 Å, and similarly the eclipse ends later for the red wing of the H lines. During eclipse in He II 4686 Å and in the Balmer lines there appears a pronounced rotational disturbance (Young and Schneider, 1980). During mid-eclipse the spectrum of the secondary companion becomes visible (Figure 3-30).

IV.B.2. OTHER DQ HERCULIS STARS

ABSTRACT: For some years the old novae V533 Her exhibited a stable pulsation like a DQ Herculis variable. In AE Aqr, a 33 sec variability could be observed ever since its detection. In most other properties AE Aqr appears to be a normal cataclysmic variable.

other nova-like stars: 96, 102, 114, 119, 125, 140

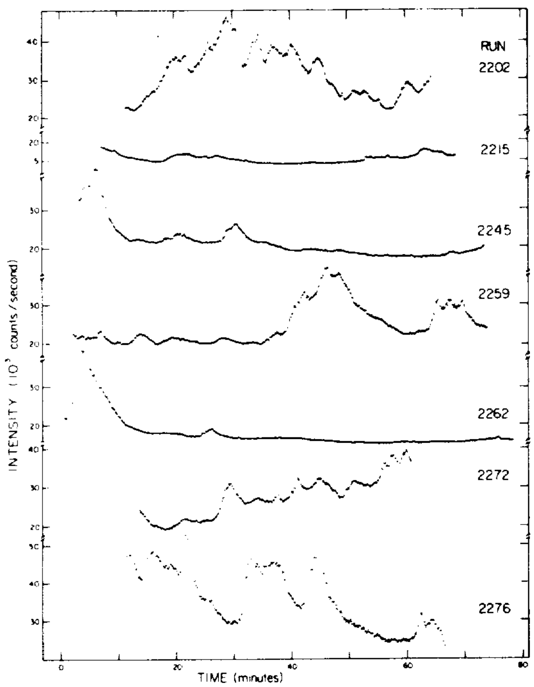
dwarf novae: 35, 46, 65

interpretation: 190

Rapid coherent oscillations of some 63 sec have been discovered in the old nova V533 Her in 1978 (Patterson, 1979a). They had a mean amplitude of 1%, were purely monochromatic, and were visible all through the orbital cycle. Observations were extended over a period of 64 days during which time the pulsations stayed strictly coherent. They also seem to have been detected in 1982 (Robinson and Nather, 1983). — When the system was observed again in 1982, there was strong flickering, but the 63 sec pulsation had entirely disappeared (Robinson and Nather, 1983).

The photometric variability of AE Aqr on time-scales of hours has been investigated extensively by Chincarini and Walker (1981). A photometric period of 9h53m is apparent in both the light curve as well as in the radial velocity curve. AE Aqr is often found in a state of pronounced flaring activity, which also seems to be responsible for the observed long-term variations (Figure 3-31). Flares occur mostly around orbital phases 0.25 and 0.8, the times of maximum and minimum radial velocity, which are also times of photometric maxima; the continuum light level remains much less affected by the flares than are the lines (Figure 3-32). Inspection of optical light curves taken at different wavelengths demonstrates that most of the activity occurs in the U-band, less in the B-band, and by far the least in V.

Investigation of the variability of the spectrum during flares revealed three types of flares: those which occur exclusively in the (mainly blue) continuum, those which occur in the wide components of the H emission lines, and those which occur in both together (Chincarini and Walker, 1981).



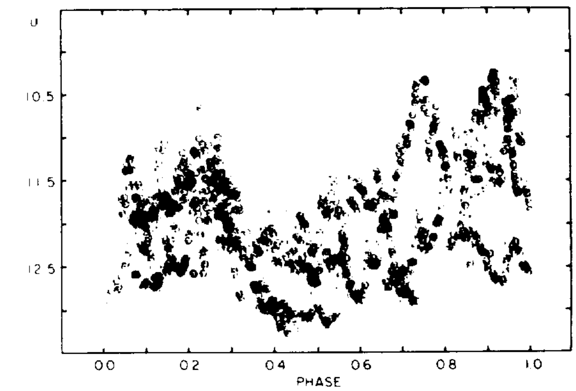
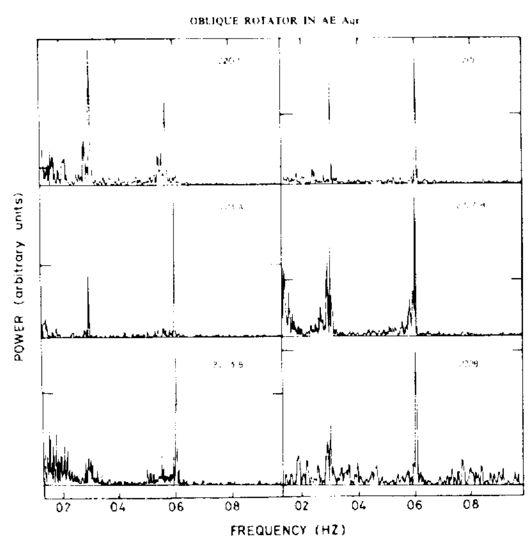


Figure 3-32. Orbital light curves of AE Aqr, measurements from different epochs (Chincarini and Walker, 1981).

Figure 3-31 (left) Light curves of AE Aqr taken at various epochs (Patterson, 1979b).



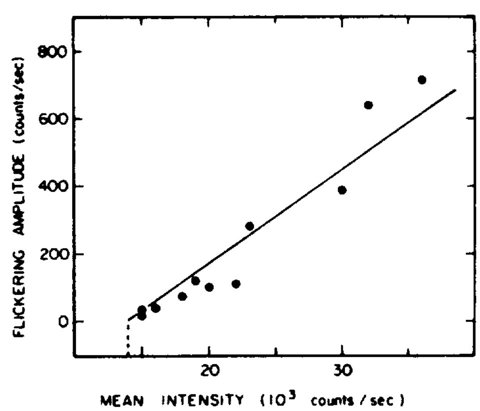


Figure 3-34. Relation between flickering amplitude and mean intensity in AE Aqr (Patterson, 1979b).

Figure 3-33. (left) Power spectra of AE Aqr (Patterson, 1979b).

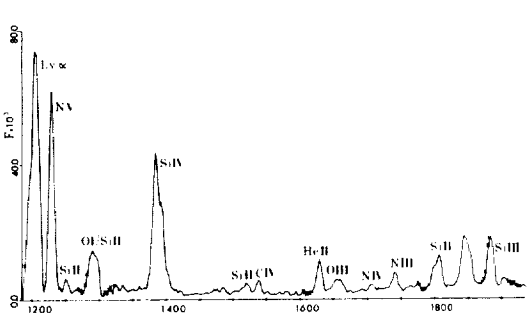


Figure 3-35. UV spectrum of AE Aqr (Jameson et al, 1980).

Power spectrum analysis of different photometric brightness levels exhibits the presence of a highly coherent oscillation with 33.08 sec period over many years, as well as a comparable, often more powerful, oscillation in the first harmonic at 16.04 sec (Figure 3-33). In addition, far less coherent quasi-periodic oscillations containing much less power can be present together with, or even instead of, the coherent oscillations — although at those times when only quasi-periodic oscillations can be detected, the latter are so strong that the simultaneous presence of the coherent oscillations cannot be excluded. Quasi-periodic oscillations only could be detected at times of enhanced flaring activity, never during minimum normal light. The amplitudes of both coherent and quasi-periodic oscillations usually are on the order of 0.1 - 0.2 % of the general flux level, though during times of strong flares they can increase to up to 2% within only some two minutes. X-ray observations in the range of 0.1 - 4.0 keV revealed the 33 sec periodicity to be present also there, agreeing in phase with the optical pulsation. Besides these more or less coherent variabilities, normal flickering can also be observed at much lower frequencies. The amplitude is well correlated with the general brightness of the system (Figure 3-34).

The optical spectrum of AE Aqr consists of a dK0 absorption spectrum as well as H, He I, and Ca II emission lines (Chincarini and Walker, 1981). In particular, the H lines show a very complex structure consisting of a wide and a narrow component. Radial velocity curves of the narrow component almost agree in phase and K-amplitude with those of the absorption spectrum, thus suggesting a common origin, whereas the wide emission component is out of phase by roughly 180°. In addition, rapid changes in radial velocity are reported which are not related to the orbital motion.

The UV spectrum of AE Aqr is very atypical for a cataclysmic variable (Figure 3-35). The continuum rises slightly towards the red from Lyα on. The line spectrum consists exclusively of emissions. N V (1240 Å), and Si IV (1400 Å) are strong, whereas C IV (1550 Å) is remarkably weak; Mg II (2800 Å) is unusually strong; emissions of Si II, Si III, N II, N IV, and He II are strongly present. There is indication for the line flux to be anti-correlated with the optical brightness of the system (Jameson et al, 1980).

AE Aqr has been detected at radio wavelengths at 15 mJy by Bookbinder and Lamb (1985, see also Chanmugam, 1987).

IV.C. INTERMEDIATE POLARS

IV.C.1. EX HYDRAE

ABSTRACT: EX Hya is a very unique object. The binary period is given by a recurring eclipse; in addition there is another period which is shorter by ⅓, most pronounced in the appearance of a recurring hump. X-rays and the line spectrum vary with both periods. Optical color variations connected with the shorter period are different from what is seen in other cataclysmic variables.

other nova-like stars: 96, 102, 114, 117, 122, 125, 140

dwarf novae: 35, 46, 65

interpretation: 190

EX Hya is a very unique object in many respects. It is closely related to dwarf novae in its outburst activity. As a DQ Herculis star, it is the only known object in which the second photometric period is close to 2/3 of the orbital period. For all other objects this parameter is either some one or some two orders of magnitude shorter than the binary period.

Power spectrum analysis of the optical data reveals two other periodicities besides the 98 and 67 min periods, one at 49.1 min which is one-half of the orbital period, and one at 46.4 min which does not have any other correspondence.

As in many other cataclysmic variables, the orbital period shows cyclic secular variations on time-scales of 10 - 14 years. The 67 min

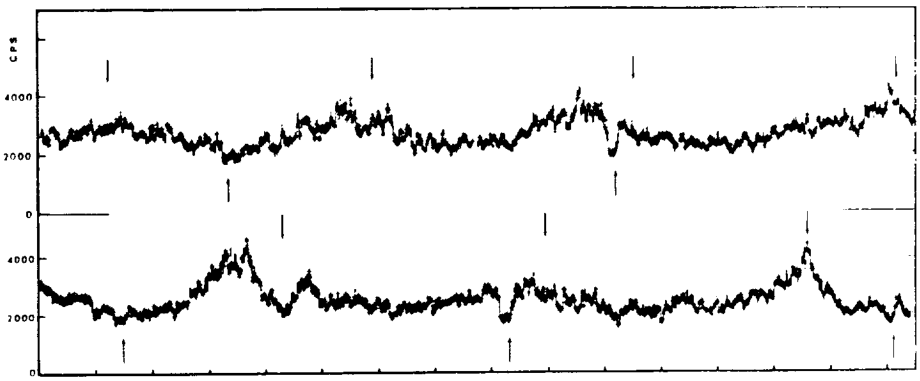


Figure 3-36. Optical light curve EX Hya (Warner and McGraw, 1981).

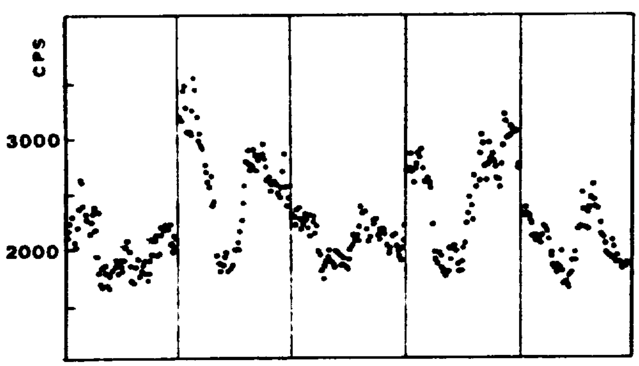


Figure 3-37. Eclipse depths of EX Hya at various epochs (Warner and McGraw, 1981).

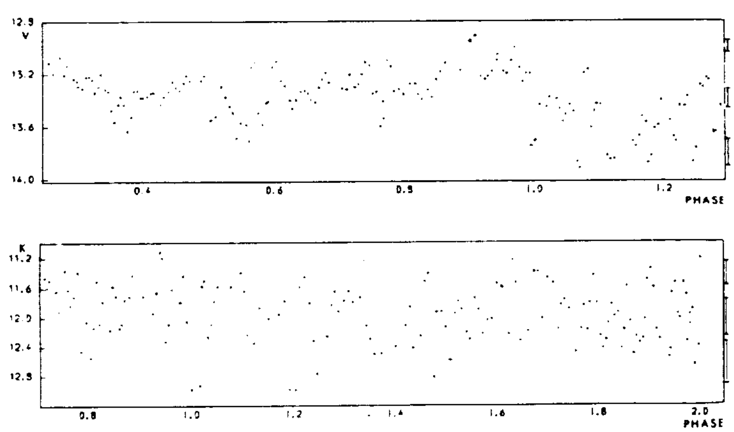


Figure 3-38. V and K light curves of EX Hya (Sherrington et al, 1980).

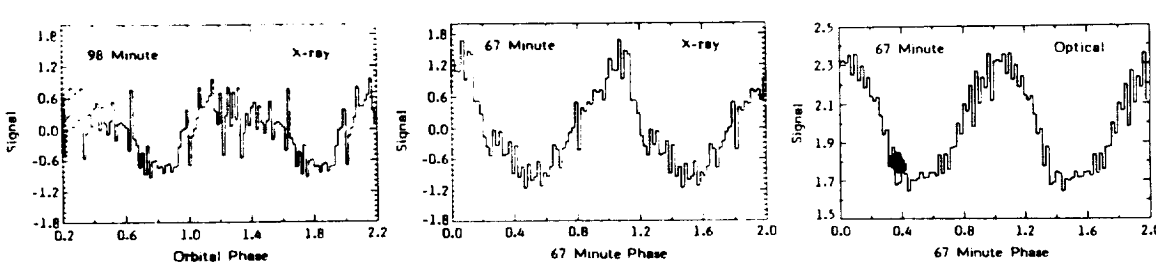


Figure 3-39. X-ray light curves of EX Hya folded with the orbital period and the 67 min period (Córdova et al, 1985).

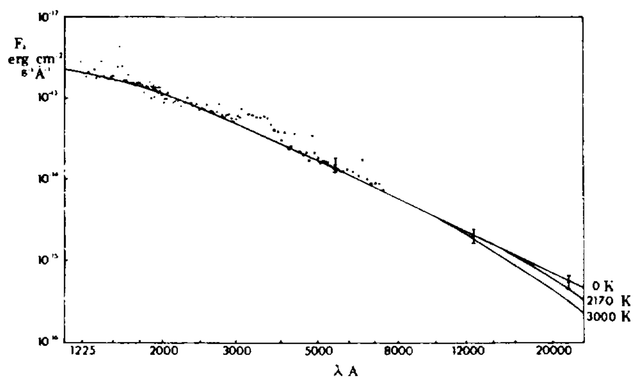
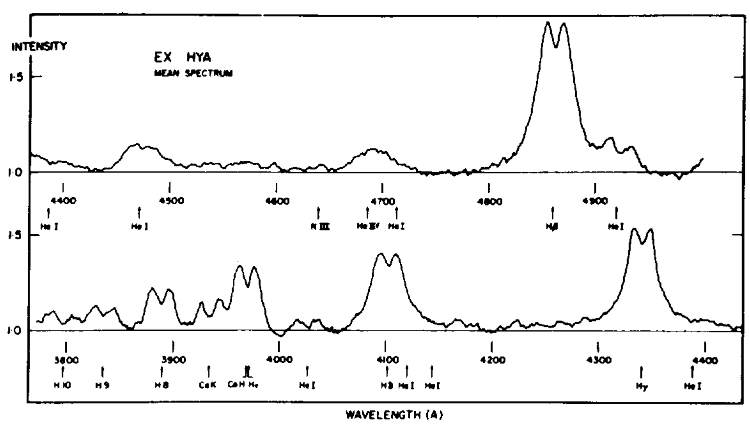


Figure 3-40. General flux distribution of EX Hya (Sherrington et al, 1980).

Figure 3-41. (below) Optical spectrum of EX Hya (Cowley et al, 1981).



period, however, clearly decreases on timescales of 10^6 years (Jablonski and Busko, 1985).

The most pronounced photometric changes in the light curve occur in connection with the 67 minute period, which appears with a hump-like feature; the brightness at hump minimum stays almost constant, although the amplitude can vary (Vogt et al, 1980). Superimposed is an eclipse phenomenon which recurs with the orbital period of some 98 minutes; furthermore, there is strong flickering and flaring activity throughout the orbital cycle (Figure 3-36; see also Vogt et al, 1980).

The eclipse has a fairly variable depth (Figure 3-37) which turns out to be related to the phase of the eclipse in the 67 min cycle: the bottom of the eclipse always reaches approximately the same brightness level, thus being shallow or almost absent at times of minimum of the 67 min cycle, and deep (up to 0.8 mag) at its maximum. Furthermore, eclipses tend to occur systematically late by up to 35 sec with respect to a mean ephemeris when they occur between phases 0.0 to 0.5 of the 67 min cycle, and systematically early by the same amount of time during the second half of the 67 min period (Jablonski and Busko, 1985).

Color changes during the 67 min hump are opposite to what is observed in dwarf novae during hump maximum: it becomes bluer during hump maximum and redder during minimum. Similar to dwarf novae, the amplitude of the hump is largest ($\sim$0.4 mag) in U and slightly smaller at longer wavelengths. Light changes in the IR do not have any obvious relation to changes in the optical, although there might be a slight dip present at orbital phase zero. No real trace of the 67 min period can be found in the IR (Figure 3-38).

The 67 min optical period is strongly visible in soft X-rays in the range of 0.1 - 2 keV with a pulsed fraction of some 30%. The orbital period of 98 min is visible too, but with a lower amplitude of only some 15% (Figure 3-39). A narrow dip corresponding to phase and duration of the optical eclipse is apparent, and there is also a broad dip around phase 0.7 which has no correspondence in the optical. The profiles of both light curves are asymmetric. At 1-4 keV the 67 min period is still visible with an amplitude of some 36%, and some 24% in 4-9 keV (Beuermann and Osborne, 1985); the only X-ray flux modulation which can be seen with the orbital period at these high energies is a 30% to 60% deep narrow eclipse at the time of optical minimum and with approximately the duration of the optical eclipse; again, individual eclipses are reported to show pronounced difference, in particular in depth, as a function of their phase in the 67 min cycle as well as the orbital period (Beuermann and Osborne, 1985; 1988). At even higher energies (kT $\approx$ 8 keV) a constant low level flux can be observed (Heise et al, 1987).

The flux distribution of EX Hya decreases monotonically from 1200 Å to 20000 Å (Figure 3-40); then however, it turns up again. The corresponding temperature between 550 and 750 K responsible for this rise is far too low to be ascribable to the secondary star (Frank et al, 1981b).

While EX Hya can by no means be closely compared with WZ Sge photometrically, both systems are fairly similar spectroscopically. EX Hya shows very strong and extremely broad (~ 7000 km/sec at the base) emission lines of H, He I, He II, and some other species (Figures 3-41). All H lines are double-peaked with a separation of 1000 - 1400 km/sec, He II 4686 Å is single peaked. The line profiles show a pronounced S-wave variation with the orbital period (Gilliland, 1982b). While there is no correlation between the equivalent widths and the orbital cycle, they vary with the 57 min period (Vogt and Breysacher, 1980a, Hellier et al, 1987). The maximum of the equivalent width closely coincides with the maximum continuum flux and the maximum X-ray flux, so the variation is not merely due to variable continuum level. Gilliland (1982b) found that the line profiles vary one half of the 67 min period as well as on the orbital period, while Hellier et al (1987) found no evidence for this from later observations. Hβ shows a pronounced rotational disturbance (Cowley et al, 1981).

IV.C.2. OTHER INTERMEDIATE POLARS

ABSTRACT: Usually more than one photometric period in addition to the orbital period can be detected in the optical. These periods are all on the order of 10 to 20 min and in every object they are remarkably similar to each other. Usually the longer period turns out to be the beat period between the shorter period and the orbital period. In most objects, one of the short periods is visible in X-rays. The spectra do not look any different from those of other nova-like stars.

other nova-like stars: 96, 102, 114, 117, 119, 125, 140

dwarf novae: 35, 46, 65

interpretation: 190

The pulsation periods of the remaining DQ Herculis stars are short enough to merely appear as photometric disturbations of the orbital light curves. None of those known so far possesses an eclipse, but all do show a hump to some extent. The recurrence times of the hump correspond to the spectroscopic periods. The short-term variability is visible in all optical wavelengths of all objects. The pulsations are monochromatic, although there might be some power in the first harmonics (e.g., Patterson and Steiner, 1983; Agrawal et al, 1984). The two pulsation periods of AO Psc occur with appreciably different power at different optical energies: at shorter wavelengths the shorter period is stronger than at longer wavelengths (Figure 3-42). When photometric observations of AO Psc are folded with all three photometric periods, i.e., 805 sec, 859 sec, and the orbital period of 3h 35.5 m, it becomes apparent that the spectral distribution of the shorter pulsational variations has about the

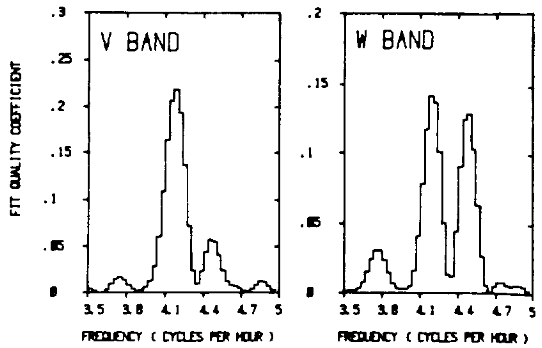


Figure 3-42. Power spectra of AO Psc in Walraven W and V bands (Motch and Pakull, 1981).

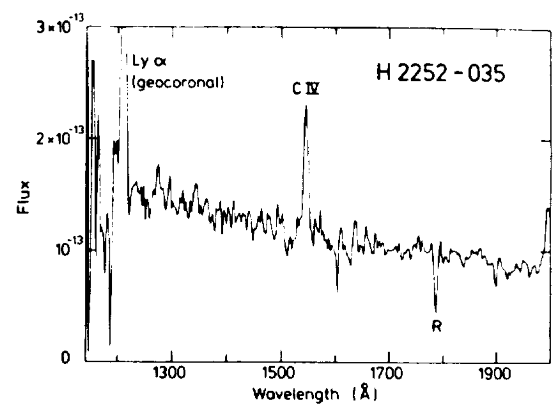


Figure 3-43. UV spectrum of AO Psc (Hassall et al, 1981).

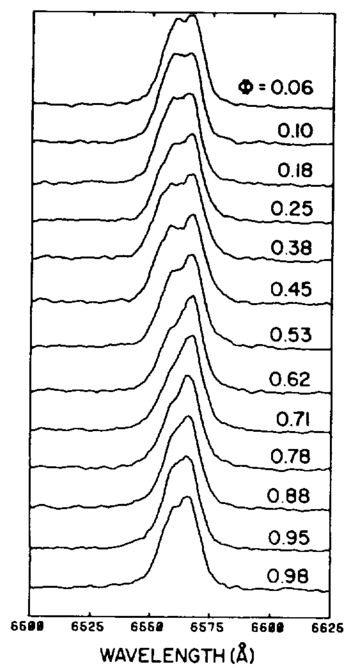


Figure 3-44. Phase-resolved optical spectroscopy of FO Aqr (Shafter and Targan, 1982).

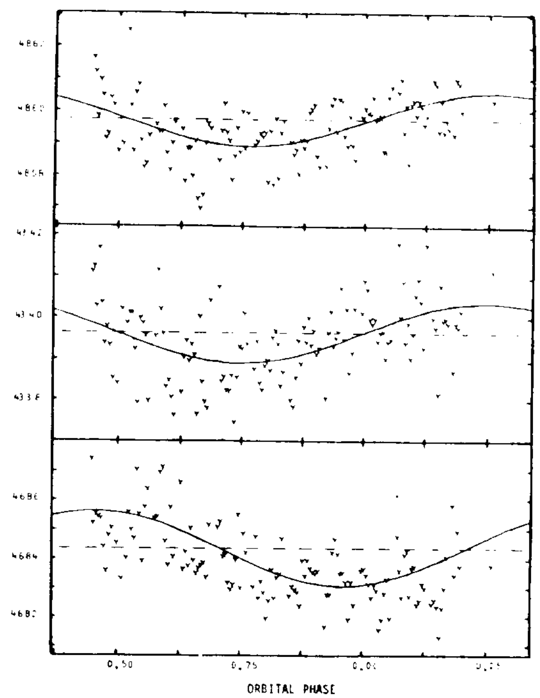


Figure 3-45. V1223 Sgr: radial velocity curves of Hβ, Hγ, He II (from top to bottom) plotted against the orbital phase (Penning, 1985).

same flux distribution as the orbital variation, while that of the longer pulsational period is different (van der Woerd et al, 1984).

In almost all of the systems, two photometric periods of comparable length have been detected besides the photometric period, and usually the longer of those two turns out to be equal to the beat period of the shorter pulsation period and the orbital period. In AO Psc, the two are in phase just after minimum of the orbital light variation and out of phase by 180% at maximum orbital light (Motch and Pakull, 1981); in V1223 Sgr the situation is just the opposite (Warner and Cropper, 1984). Also in AO Psc there are some indications that the 805 sec period is rather a transient phenomenon, which seems to be absent at times, whereas the 859 sec period is always present (van der Woerd et al, 1984). In V1223 Sgr the 745 sec period is detectable at IR wavelengths, not so the 746 sec variation (Watts et al, 1985). In V1223 Sgr and FO Aqr a secular decrease of the short photometric periods was detected with $\dot{P}$ on the order of several times 10^{-11} years (van Amerongen et al 1987a; Jablonski and Steiner, 1987; Shafter and Macry, 1987).

While usually the spectroscopic and one of the photometric periods are identical, in TV Col there is no photometric period equal to the orbital period of the system (Hutchings et al, 1981). In this respect it is similar to the anti-dwarf nova TT Ari and, possibly, to the dwarf nova CN Ori (see Chapters 2.II.B.3, 3.III.A.2).

In TV Col, FO Aqr, AO Psc, and V1223 Sgr, a pulsation period has been detected in hard X-rays. In V1223 Sgr this is a period which is not seen in the optical: the optical shows pulsations of 14.61 and 13.24 min, in the X-rays only a period of 12.4 min can be seen (Osborne et al, 1985). In the other three systems the X-ray pulsation period is equal to the shorter of the optical pulsation periods (e.g., Lamb, 1983; Cook et al, 1984; Schrijver et al, 1985). The X-ray pulsation and the respective optical one are in phase in all systems within the limits of observations. Amplitudes of the X-ray pulsation vary between some 20% and some 90%. In none of the systems has an appreciable flux been found in soft X-rays.

The optical and UV spectra of the intermediate polars do not look any different from "normal" spectra of cataclysmic variables, with all lines in emission, and a normal continuous flux distribution (e.g., Hutchings et al, 1981; Hassall et al, 1981; Kitamura et al, 1983; Warner, 1983; Mateo and Szkody, 1985; Watts et al, 1985). The UV spectrum of AO Psc is remarkable only in that there are no strong lines besides C IV (Figure 3-43). On one occasion when TV Col showed a brief outburst in both optical and UV, C IV and Si IV developed P Cygni profiles (Szkody and Mateo, 1984). In all systems, there are line profile changes in phase with the orbital revolution. FO Aqr shows line profile variations in Hα which are reminiscent of an S-wave, but they are restricted to only the blue wing of the line (Figure 3-44). The line flux in AO Psc is reported to be variable also on the 859 sec period (Motch and Pakull, 1981).

Radial velocities in BG CMi and V1223 Sgr show different phasings within the orbital period for the H, and He II lines, respectively (Figure 3-45); indications for this to be the case are also given in AO Psc and FO Aqr (Hutchings et al, 1981; Penning, 1985). The line fluxes in FO Aqr vary with the orbital period, while there is indication for the line profiles to vary on the 21 min pulsation period (Shafter and Targan, 1982). The C IV 1550 Å line flux in TV Col varies with the orbital phase (Mateo and Szkody, 1985).

GENERAL INTERPRETATION: The white dwarf in DQ Herculis stars is believed to possess an appreciable magnetic field. It is not strong enough, however, to keep the star in synchronism with the orbital revolution. The star accrets preferentially onto its magnetic poles which then become X-ray radiators. As they sweep around due to the white dwarf's rotation they produce a hot area on the inner side of the accretion disc and/or on the surface of the secondary star, which photometrically are seen as further periodicities in the light curves.

OBSERVATIONAL CONSTRAINTS TO MODELS:

- *Possible additional photometric periods seem to be constrained to values either about one or about two orders of magnitude smaller than the orbital period.*

- *EX Hya is an exception to this.*

- *The shorter photometric period, which is not the orbital period, has been seen to decrease secularly in some objects.*

- *Two or possibly three, systems are known in which none of the photometric periods is identical to the spectroscopic period.*

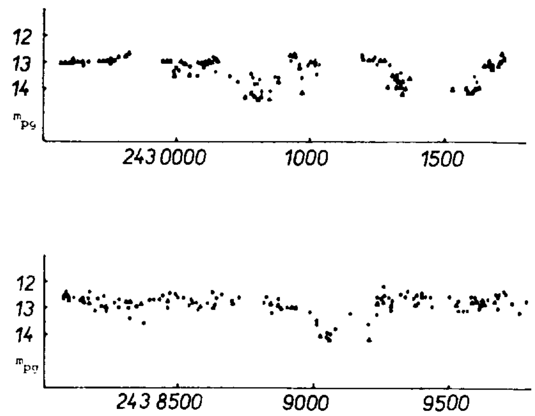


Figure 3-46. Long-term variations of AM Her (Hudec and Meinunger, 1976).

V. AM HERCULIS STARS

AM Herculis stars (polars) are distinguished from other cataclysmic variables by exhibiting very strong optical polarization (up to 30% or more has been observed) which is variable in strength with the same period as the flux at all observable wavelengths, as the radial velocity, and as the line intensities.

V.A. PHOTOMETRIC APPEARANCE

V.A.1. LONG-TERM VARIATIONS

ABSTRACT: The long-term variability is very similar to that of anti-dwarf novae in showing mostly high (in the case of AM Herculis stars they often are called "on") and low (called "off") states.

other nova-like stars: *96, 102, 114, 117, 119, 122, 140*

dwarf novae: *35, 46, 65*

interpretation: *188*

The long-term variability of AM Herculis stars is similar to that of DQ Herculis stars or anti-dwarf novae: most of the time they can be found close to some "high" (or "on") brightness level; at irregular intervals of time, typically on the order of months or years, the brightness drops by about 2 to 3 mag to the "low" (or "off") state, where it will stay for typically a hundred to a few hundred days, possibly exhibiting some brightness variation as well before returning to the bright state (Figure 3-46). In addition VV Pup was once observed at a high state that was even brighter by some 0.3 mag than the normal high state; and AN UMa and DP Leo were found in unusually low states, which in the case of AN UMa was some 2 mag fainter than the normal low. DP Leo, which is extremely faint in any case, became almost undetectable below some 20 mag (Liebert et al, 1982a; Biermann et al, 1985). Furthermore, VV Pup did not brighten above 15 mag since 1960, although the "normal" bright state until then had been around 14.4 mag (Liebert et al, 1978). The transition between high and low states is not abrupt like in dwarf novae, but is instead very gradual, taking at least a few tens of days. No periodicity in this movement between states could be detected in any AM Herculis star. Dexter et al, (1976) claim to have found a tendency for drops in brightness in AM Her to occur about every 670 days; however, investigations by means of periodogram analysis carried out by Feigelson et al, (1978) and based on observations from 1890 to 1976 did not reveal any significant periodicity in the range between 2 and 10^4 days.

V.A.2 PHOTOMETRIC CHANGES IN THE HIGH AND LOW STATES

ABSTRACT: Orbital variations are very dissimilar to those observed in other cataclysmic variables, consisting mostly of continuous variation, with no clear *distinction between hump and interhump phases possible. The appearance of the light curve is highly color dependent. So far only one object is known to show a brief total eclipse, the shape of which again is atypical for a cataclysmic variable. Flickering and flaring are very pronounced. Quasi-periodic oscillations occur. — During off states the appearance of an object can vary strongly from one night to the next. The strong X-ray radiation varies synchronously with the optical light.*

other nova-like stars: 96, 102, 114, 117, 119, 122, 140

dwarf novae: 35, 46, 65

interpretation: 188

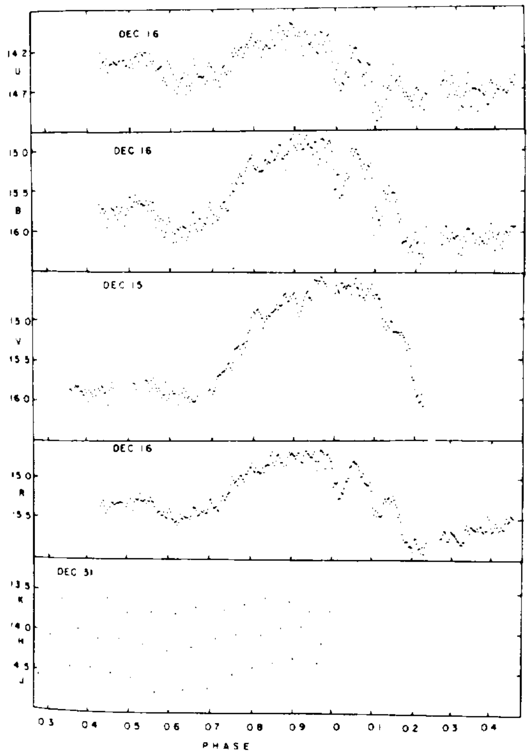
The stable photometric periods of AM Herculis stars — which turn out to be the orbital periods of the systems — are typically on the order of one to two hours, although the periods of some AM Herculis stars (AM Her, H0538 + 608, QQ Vul) lie above the period gap of cataclysmic variables. The light curves, although they are quite different from one object to another, are mostly very dissimilar from those of other cataclysmic variables: a distinction between hump and interhump phase is hardly possible, since the light keeps changing all the time; between one and three minima (or maxima) per cycle can be distinguished in different objects; and, also much unlike in other objects, the shape of the light curves is highly dependent on the wavelength. Typical optical and IR light curves of an AM Herculis system, VV Pup, are given in Figure 3-47a (more examples can be found in Gilmozzi et al, 1978; Raymond et al, 1978; Szkody and Capps, 1980; Frank et al, 1981a; Miller, 1982), and a schematic set of curves of EF Eri is given in Figure 3-47b. As for instance in the examples of Figure 3-47, the phases of the minima of the light curves in some objects are strongly dependent on wavelength, which indicates that these are probably not eclipses as observed in many other nova-like stars and dwarf novae; in others, like MR Ser or QQ Vul, they all occur at roughly the same phase at all energies. In BL Hyi the brightness variability in U seems to be anticorrelated to that in V (Thorstensen et al, 1983).

Corresponding to the wavelength dependence of the light curves, and again much unlike other cataclysmic variables in which the optical colors hardly vary outside the times of eclipse, the color curves are highly variable with phase, and reasonably well-defined loops in the color-color diagram are performed. All systems seem to become redder consistently during the brighter orbital phases, which merely is a reflection of the amplitude increase with increasing wavelength.

The exact shapes of the light curves of all these objects are variable from one cycle to the next and even more so on time-scales of months or years (only referring to the "normal" high state so far); an example is shown in Figure 3-48 (see also Cropper et al, 1986). Mostly the shape and amplitude of the maxima is affected, while the minimum light level is much less variable. Phase shifts of the minimum in U light by 0.3 in phase have been reported for AM Her (Szkody, 1978; Visvanathan and Wickramasinghe, 1979).

The amplitudes of the brightness changes with orbital phase in all AM Herculis stars are smallest in U and increase considerably toward longer wavelengths, and the variability in U is often only poorly correlated with the more synchronized behavior at lower energies and is the most sinusoidally shaped (Figure 3-47). At very low energies the light variation again becomes largely independent of that in the optical and near IR: The K-light curves (2.2 μ) in VV Pup and EF Eri are again almost sine-like. One exception to this is the system QQ Vul, in which the light curves are very similar in shape and amplitude in all wavelengths from U to I (Figure 3-49), with the exception of the variations around the minimum at about phase 0.4 which become increasingly ill-defined at longer wavelengths.

The only AM Herculis star which really is an eclipsing variable is DP Leo (Figure 3-50): for about 4 minutes around phase 0.71 the flux in the optical as well as the X-rays drops to zero.



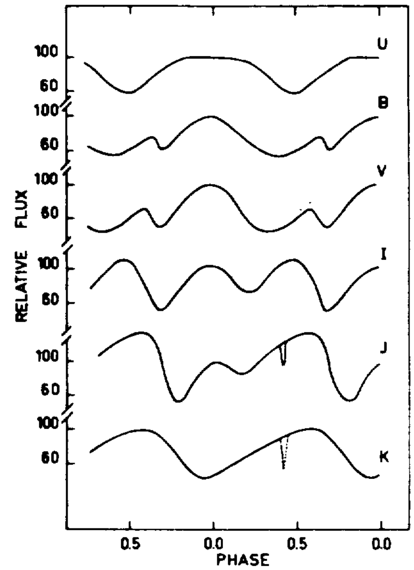


Figure 3-47b. (above) Schematic optical light curve of EF Eri in different colors (Motch et al, 1982).

Figure 3-47a. (left) Optical light curve of VV Pup in U, B, V, R, K, H, and J light (top and bottom) (Szkody et al, 1983).

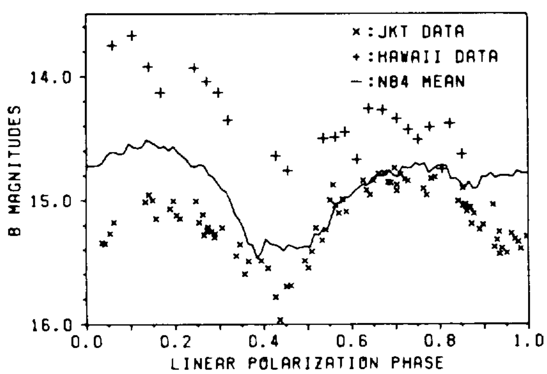


Figure 3-48. Variability of the optical appearance of QQ Vul on long time-scales (Mukai et al, 1986).

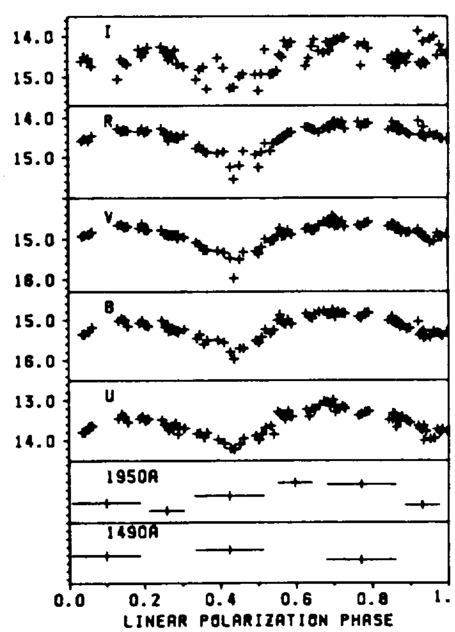
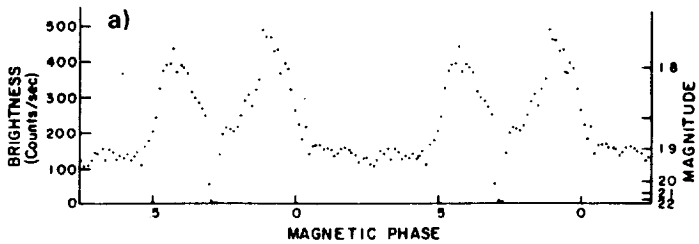


Figure 3-49. Optical light curve of QQ Vul in various colors (Mukai et al, 1986).

Unlike eclipses known in other cataclysmic variables, this one is very symmetric, ingress and egress both last for equally long times (somewhat less than 40 seconds), and there is no preceding hump, nor is there any detectable hold during ingress or egress, as always occurs for total eclipses in other cataclysmic variables. The optical light and the polarization are strictly locked to each other in phase.



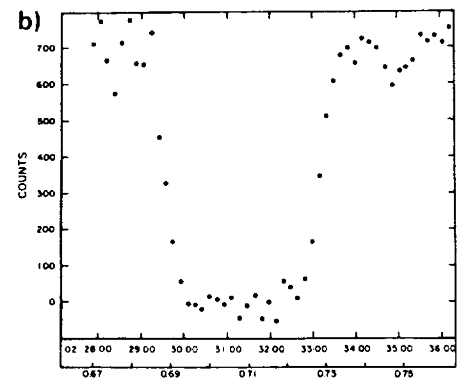


Figure 3-50. (a), optical light curve of the eclipsing system DP Leo and (b) enlarged presentation of hte eclipse shape (Biermann et al, 1985).

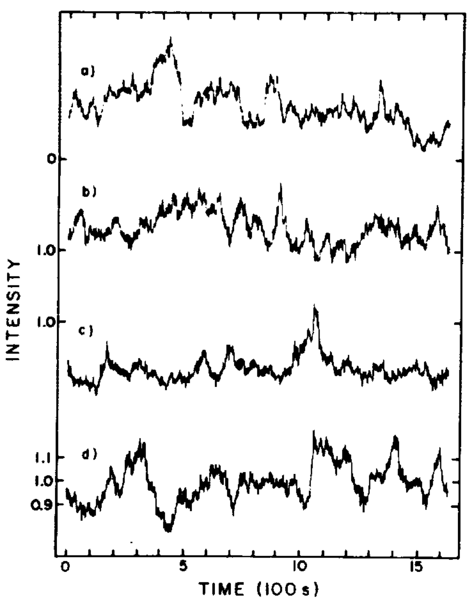


Figure 3-51. Optical flaring activity in AM Her (Panek, 1980).

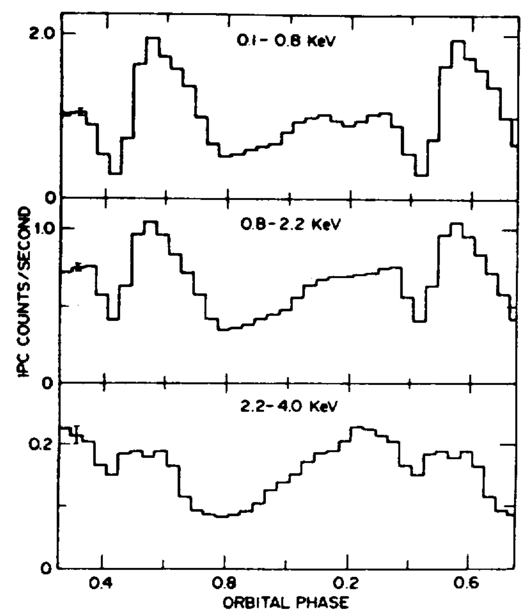


Figure 3-52. X-ray light curves of EF Eri in different energy bands (Patterson et al, 1981a).

In addition to orbital variations, flickering activity is observed in all systems. It is present with equal strength at all orbital phases. Similar to other cataclysmic variables, amplitudes range from just 0.1 to 0.3 mag in AM Her to 0.8 to 1.0 mag in VV Pup, and time-scales are on the order of a couple of minutes. In AM Her the flickering at different optical and infrared wavelengths has been found to be correlated: the main peaks seem to occur simultaneously at all wavelengths with U slightly leading the lower energies (Bailey et al, 1977; Olson, 1977; Szkody and Margon, 1980).

Another sort of irregular activity in AM Herculis stars is the so-called "flaring," which occasionally can also be observed in some other cataclysmic variables, but then with a higher amplitude (e.g., SS Cyg and RW Tri, chapters 2.II.D.1, 3.II.A.2). This term refers to rapid irregular brightness increases by some tenths of a magnitude every couple of hundred seconds, lasting for about one minute (Figure 3-51). It seems to occur simultaneously at all wavelengths. The amplitude increases toward longer wavelengths. No periodic behavior in this phenomenon could be detected over longer

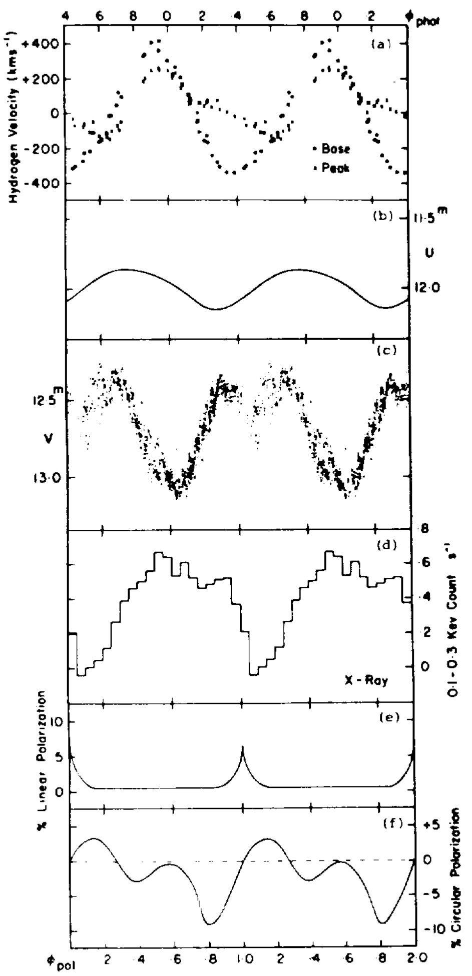


Figure 3-53. Phase relations between photometric and polarimetric variations of AM Her (Crampton and Cowley, 1977).

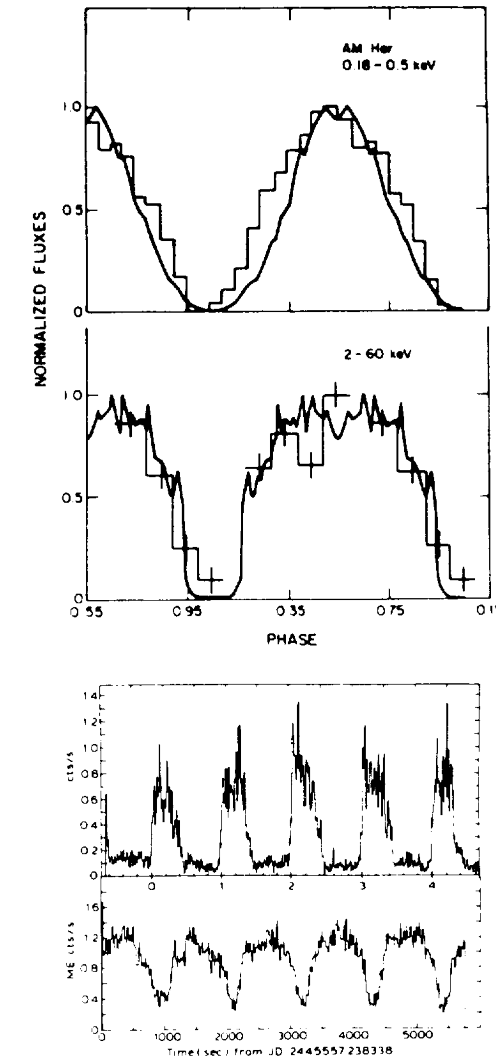


Figure 3-54. X-ray light curves of AM Her in (a) normal high and (b) reversed high modes (a: Imamura, 1984; b: Heise et al, 1985).

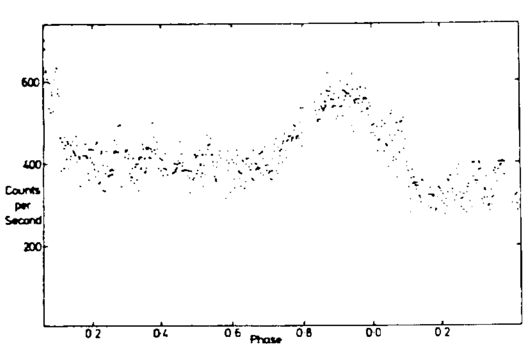


Figure 3-55. Optical light curve of VV Pup in the low state (Bailey, 1978).

time-scales. The distinction between flickering and flaring is one of amplitude and frequency. In one object the distinct flares have somewhat higher amplitudes than the flickering which is always present; their amplitude may, however, well be of the same order as the flickering in some other object.

Periodic variabilities on time-scales of seconds, which are very strong and common in many dwarf novae, occur only rarely in AM Herculis stars. Quasi-periodic oscillations in the range of 1.25 to 2.5 sec once were found in

V834 Cen, in AN UMa, and in EF Eri with powers of a few percent, respectively; whereas no trace of this could be detected in AM Her (Middleditch, 1982; Larsson, 1987; Cropper et al, 1986). Other observations of AM Her revealed the simultaneous presence of many, though not very strong, monochromatic spikes in the power spectra with periods between 62 and 450 sec, reminiscent of the coherent oscillations in dwarf novae; these did not repeat from night to night (Berg and Duthie, 1977). Szkody (1978) reports oscillations of 197 sec and 512 sec to have been present during four consecutive nights, while an oscillation of 426 sec only could be found around phase 0.3; in addition, she also found many highly transient monochromatic spikes in the power spectra for periods between 27 and 1280 sec. On different occasions, a quasi-periodic oscillation near 6 minutes was found in EF Eri which was also seen in X-rays and circular polarization (Williams and Hiltner, 1980; Crampton et al, 1981; Patterson et al, 1981a; Williams and Hiltner, 1982). At other times, however, no oscillation whatsoever could be seen, or oscillations appeared with very different periods, similar to what occasionally is observed in AM Her. Furthermore, different oscillations were seen in different wavebands (Bond et al, 1979; Motch et al, 1982).

All AM Herculis stars are strong, and variable sources of both hard and soft X-rays. The variability at all X-ray energies is strictly synchronous with the variability in the UV, optical, and IR, as well as with spectrum and polarization changes. The shape of the light curve varies with the energy band, as in the optical (Figure 3-52). Except for relatively minor changes, the shape of the light curve at any energy seems to be rather stable for a longer time; in particular, the phase relation between individual features in the optical light curves and the X-ray light curves remains constant over many years (Swank et al, 1977). The X-ray light curves of different objects are remarkably dissimilar, often resembling the respective optical light curves.

As an example, the phase relations between different, periodically variable properties of AM Her are shown in Figure 3-53; similar relations exist in all other AM Herculis stars as well. In the particular case of AM Her, the X-ray eclipse, which is total, almost coincides with the partial optical secondary eclipse, whereas no X-ray minimum occurs at the time of the optical primary minimum. Similarly, it can be seen that at the time of the X-ray eclipse there is a hold in circular polarization and ingress which coincides with the strong pulse in linear polarization (see also below). In the eclipsing system DP Leo, the X-rays are eclipsed at exactly the same time as the optical flux. In DP Leo, ST LMi, and VV Pup, the X-ray flux is zero for almost half of the orbital period, exhibiting just one hump for the rest of the time (Patterson et al, 1984; Beuermann and Stella, 1985; Biermann et al, 1985). A dip in the X-ray flux occurs in VV Pup around phase 0.94, at the same time when a small dip is also seen in the optical. In EF Eri, a narrow eclipse feature can be seen in J and K around phase 0.42, which is not present at optical wavelengths (Figure 3.47b); during this same phase, as will be shown later, the emission lines longward of 5500 Å all go into absorption; and at X-rays, centered at around phase 0.43, a narrow eclipse feature can be seen which is total for energies between 0.1 and 0.8 keV, and not visible at all for energies above 3 keV (Patterson et al, 1981a).

Some flickering does occur at X-rays as well. In most cases there seems to be no correlation, however, with times and amplitudes of flickering in the optical. In EF Eri, however, it was found that the correlation between flickering in hard X-rays and the optical is very strong, while it is much weaker between soft X-rays and the optical (Crosa et al, 1981; Crampton et al, 1981; Patterson et al, 1981a; Singh et al, 1984; Beuermann and Stella, 1985; Watson et al, 1987).

Two very unusual events have been reported for the X-rays of AM Her. In 1976 the optical secondary minimum had disappeared. The X-ray flux was variable by about a factor of 2, but any pattern occurred at random and at other times strict periodicity was lost; optical and hard X-ray flux were at their average high level, whereas the soft X-ray flux had decreased by a factor of 3 (Priedhorski, 1986).

In 1983 and 1984, on different occasions, the system was observed to display a previously unknown kind of X-ray light curve, shown in Figure 3-54: The hard X-rays reached a minimum periodically at the same orbital phase as was seen in previous observations for energies above 1 keV, and the shape of this light curve also remained roughly the same. However, in former observations of the soft X-rays the flux variation had been almost sinusoidal with the minimum coinciding with that observed in hard X-rays, in this so-called "reversed mode" it showed very distinct high and low levels, each lasting for about half a period, with very short transition times of only 2 to 3 minutes. The center of the highly variable high phase was seen to coincide with the minimum of the hard X-ray flux. Rise to the high level occurred at phase 0.95, i.e., before maximum of the linear polarization pulse (see below).

Between different events of the reversed mode the system briefly returned to the normal mode (still at high level of the optical flux) and then to optically low level. During both the reversed and the normal high mode, optical photometric observations were carried out which in no way appeared peculiar when compared with each other or former observations (Mazeh et al, 1986).

Osborne et al (1987) report remarkably similar dramatic changes to have occurred in the systems QQ Vul in 1985. Here the relative fluxes in X-rays, UV, and optical changed appreciably, together with the shape of all the light curves: the x-ray light curve in 1985 looked strikingly similar to that of AM Her in reversed mode.

During the rare faint states the optical light curves of AM Herculis stars become very irregular or smoothed out while the IR is much less affected (Figure 3-55; see also e.g., Szkody, 1978; Allen et al, 1982; Szkody et al, 1982b; Tuohy et al, 1985). The minima and maxima which are easily seen during high state practically disappear in the optical, in particular since the flickering usually remains strong. In BL Hyi, narrow minima appear around phase zero, which, however, are not separated by one orbital period and thus have no geometric origin (Tuohy et al, 1985). In VV Pup in low state, no significant hump in the light curve could be seen during observations of one night, whereas it was clearly present on the following night (Bailey, 1978). Similar behavior has been reported for other AM Herculis stars (e.g., Szkody et al, 1983).

During the optically low state the flux in both hard and soft X-rays drops as well. The synchronous variations of the X-rays with the optical variations remains. In AM Her, the eclipse in soft X-rays is reported to disappear (Priedhorski and Marshall, 1982); otherwise, no dramatic changes are reported for any other object other than a decrease in flux level (this may be due to lack of data since, even for otherwise bright objects, the x-ray flux is too low to be measured accurately during the low state).

V.B. POLARIZATION

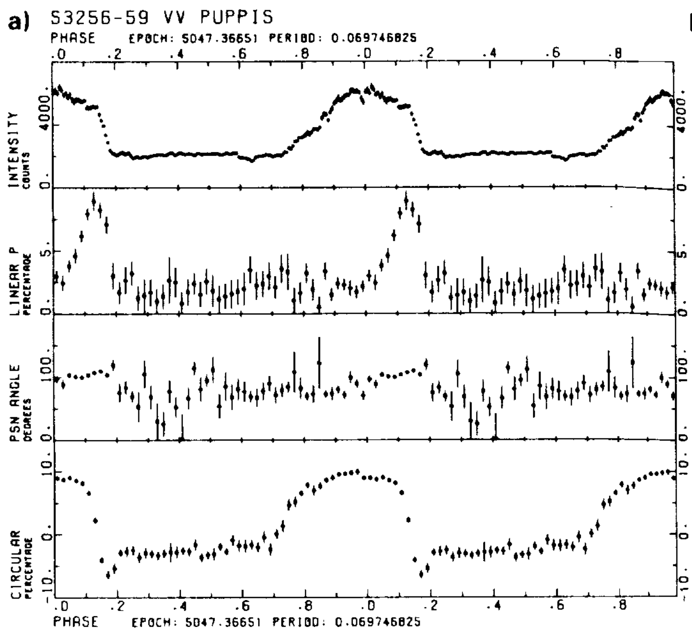
ABSTRACT: The systems exhibit up to 30% circularly and linearly polarized radiation. Strong variations in the degree of polarization occur synchronously with spectroscopic and photometric variations.

other nova-like stars: 98, 106, 113

dwarf novae: 64

interpretation: 188

AM Herculis stars emit very strong and strictly periodically variable circularly and linearly polarized radiation, very much unlike



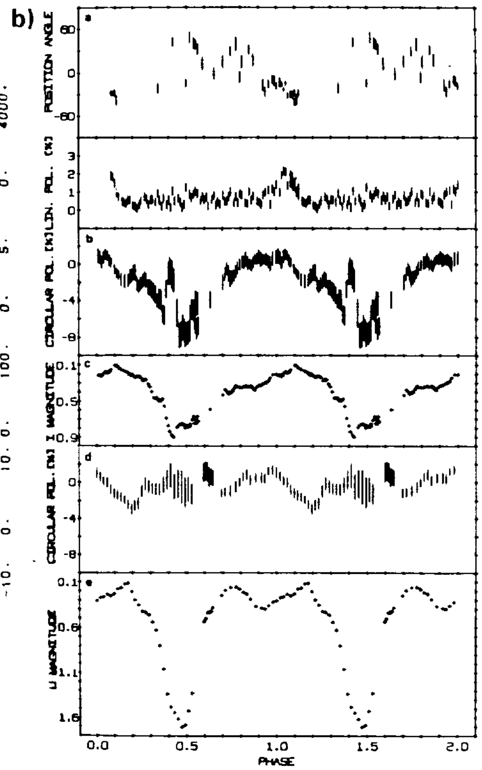


Figure 3-56. Phase relations between photometric and polarimetric variations in (a) QQ Vul and (b) VV Pup (A: Nousek et al, 1984; b: Cropper and Warner, 1986; see also Figure 3-53).

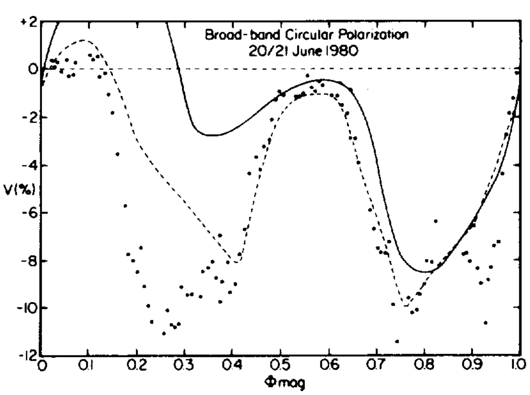
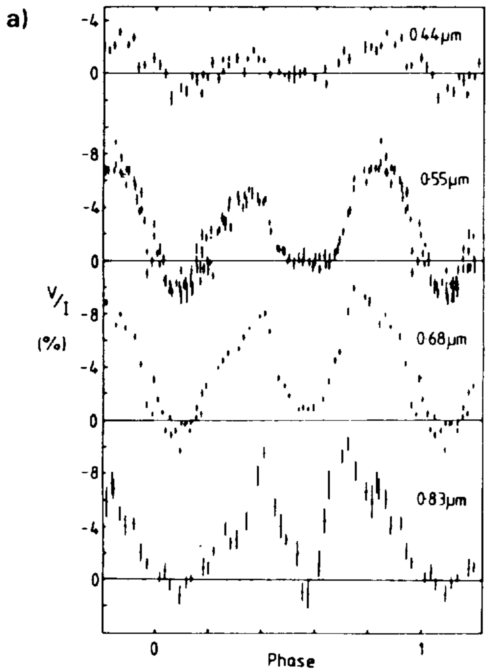
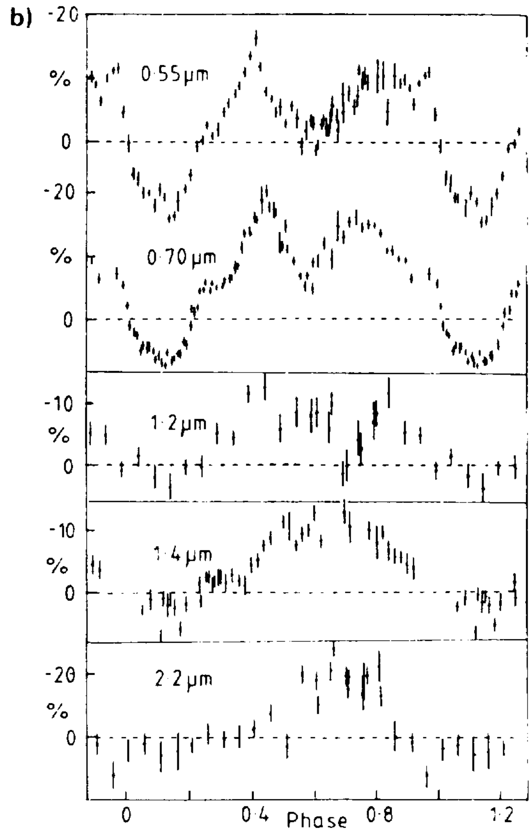


Figure 3-57. Circular polarization of AM Her in the low state (filled circles), and the high state (dashed line: Bailey and Axon, 1981; solid line: Young and Schneider, 1979) (Latham et al, 1981).

other nova-like stars or dwarf novae for which the level of polarized flux is typically on the order of 0.3% if detected at all. The variability follows the same periodicity as any other orbital variabilities in AM Herculis stars, wherein the polarization curve usually exhibits a fairly intricate but stable pattern. Examples of polarization curves and their phase relations to other variable properties are shown in Figure 3-56 (other examples can be found in, for instance, Allen et al, 1981; Liebert et al, 1982b; Biermann et al, 1985; Cropper, 1986). The circular polarization typically varies with an amplitude of up to 10 - 30% of the flux, the linear polarization by about half this value. With the exception of ST LMi, which exhibits two spikes in linear polarization, usually only one sharp spike in linear polarization is observed per orbital cycle in AM Herculis stars. By convention, normally the maximum of this for all orbital variability is defined as phase zero.

The linear polarization pulse lasts for about one to two tenths of the orbital cycle, depending on the object. Between two consecutive





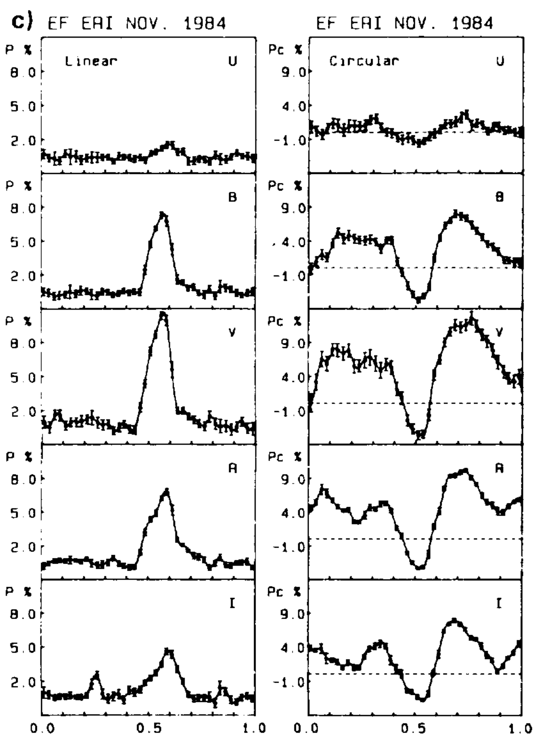


Figure 3-58. Wavelength dependence of optical and IR polarization in a: AM Her (Bailey and Axon, 1981); b: AM Her (Bailey et al, 1984); c: EF Eri (Piirola et al, 1987), all during the high state.

pulses the linear polarization usually is zero or close to this. In EF Eri, Allen et al (1981) report an occasionally present secondary peak in linear polarization around phase 0.4. In ST LMi, the linear polarization is strong throughout the brighter states of the optical flux during the orbital cycle, displaying a spike at the beginning and at the end of it (Stockman et al, 1983; Cropper, 1986). Usually though not always, in AM Herculis stars the peak in linear polarization coincides with either a zero-crossing of the circular polarization or with the time when the circular polarization is close to zero, which usually is also the time of higher optical flux, and often coincides with a dip in soft X-rays. The position angle of the linear polarization periodically performs systematic changes in size with the orbital period.

The shape of the circular polarization curve usually is fairly complex, exhibiting several relative minima and maxima during one cycle. For most objects it is either mostly or entirely either negative or positive, showing polarization of the other sign for only a short time and with a distinctly lesser degree of polarization. Though its shape is characteristic for each object, it is variable over longer time-scales, in particular when dropping to low optical flux, as has been shown in the case of AM Her by Latham et al (1981) and (Figure 3-57). The linear pulse is also subject to changes in amplitude on longer time-scales.

Like the optical flux, both the linear and circular polarization are strongly color dependent (Figure 3-58; see also Figure 3-56, Krzeminski and Serkovski, 1977; Bailey et al, 1982; Szkody, 1985; Piirola et al, 1987). The variability usually is small in U, increasing in amplitude toward longer wavelengths up to 6000 to 8000 Å (depending on the object), then slowly decreasing again, but it still is readily measurable at 20000 Å. In the course of years the shape of the polarization curve changes significantly, like the light curve (e.g., Figure 3-57; Cropper et al, 1986, Remillard et al, 1986).

V.C. SPECTROSCOPIC OBSERVATIONS IN THE HIGH AND LOW STATES

ABSTRACT: The general appearance of AM Herculis stars is not very different from that of other cataclysmic variables. Almost pure emission line spectra are observed. The hydrogen lines mostly consist of a broad base and a narrow peak component which vary independently of each other. The narrow component still can be seen during the low state. Also during low state absorption features become visible which are identified with Zeeman lines. The absorption spectrum of a cool companion is seen in some objects. Radial velocity variations (in high and low states) are synchronous with photometric and polarimetric variations.

other nova-like stars: 99, 107, 116, 119, 122, 124, 141

dwarf novae: 65

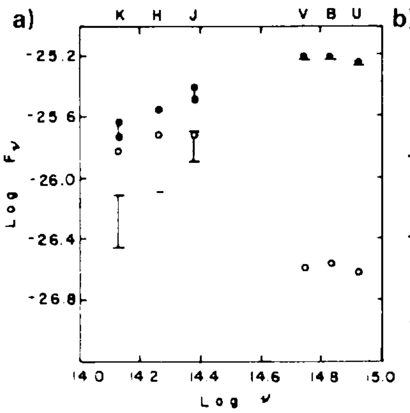
interpretation: 151, 192

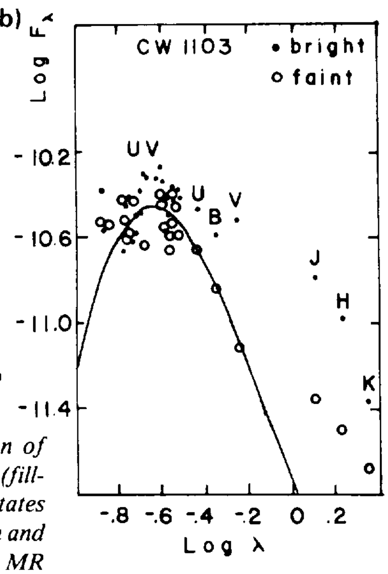
The overall flux distributions of three typical AM Herculis stars are shown in Figure 3-59. Statistically the flux distribution is not dramatically different from that of other cataclysmic variables. Clearly no fit of the entire spectrum with one black body or a power law is possible, even when restricted to only optical and UV wavelengths; several different components contribute to the observable flux. With regard to the transition from high to low state, the effect is different in different objects: in VV Pup for instance, strong changes occur in the optical, while changes are rather small at IR wavelengths; in ST LMi on the other hand, changes are most appreciable in the IR, while they are a lot smaller in the optical.

A positive detection at radio energies has so far only been possible for AM Her, although several other AM Herculis stars have been looked at (Dulk et al, 1983). AM Her was detected at 4.9 GHz with no obvious flux variation correlated with the orbital phase being present (Chanmugam and Dulk, 1982; Bastian et al, 1985). At no time could AM Her be detected at either 1.4 or 16 GHz, not even during the 4.9 GHz outburst.

The X-ray spectrum of AM Her obviously consists of two components: a strong soft component with maximum flux around 0.2 keV, and a much weaker hard component which fades toward higher energies and becomes undetectable below 100 keV (Figure 3-60). Similar tendencies, though not measured that accurately, are seen in other AM Herculis stars. In AM Her and EF Eri, an emission feature at 6.5 ± 1.5 keV is easily visible. Both spectra were observed during optical high state.

Optical and UV spectra of AM Herculis stars are shown in Figure 3-61. In the optical as well as in the UV, the spectra are characterized by either a flat continuum or one which rises toward the IR. Superimposed are very strong emission lines of the usually visible resonance lines, of H, He I, and He II, as well as of C II, C III, C IV, Si IV, N III, N V, Fe II, etc.; i.e., the average ionization potential is somewhat higher than for other nova-like stars or dwarf novae. In particular it is noteworthy





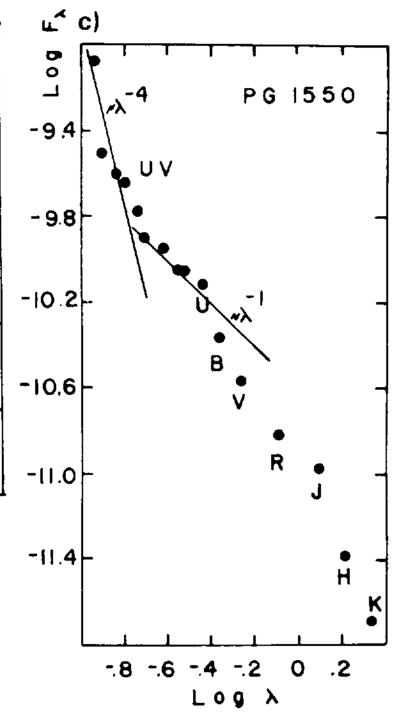


Figure 3-59. General flux distribution of AM Herculis stars: a: VV Pup in high (filled circles) and low (open circles) states (Szkody et al, 1983); b: ST LMi in high and low states (Szkody et al, 1985); and c: MR Ser (only high state known) (Szkody et al, 1985).

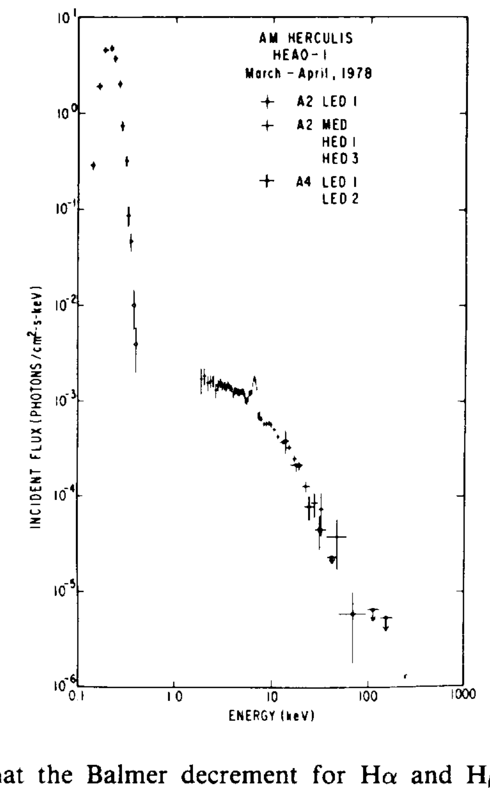


Figure 3-60. (left) X-ray spectrum of AM Her (Rothschild et al, 1981).

that the Balmer decrement for Hα and Hβ usually is either very flat or even reversed, and the flux in He II 4686 Å is often on the order of, or even larger than, that in Hβ. No forbidden lines are detectable. The UV spectrum of H0538 + 608 was found to have changed significantly within one year (Bonnet-Bidaud and Mouchet, 1987).

When traced over a full orbital cycle, the spectra show marked variability synchronous with the orbital period (Figure 3-62). The line flux is strong for about half the orbital period, centered at the time of the linear polarization pulse, and then it drops considerably, often very quickly, around phase 0.4 for some time, although ratios of line intensities hardly seem to be affected; recovering toward higher intensities takes longer than the drop (Figure 3-63). In EF Eri, lines longward of 5500 Å (including Hα) even go into absorption for a while around phase 0.45 (Biermann et al, 1985). In many objects these changes are accompanied by changes in the continuum flux (e.g., Visvanathan and Wickramasinghe, 1981), as is also reflected in the photometric light curves. No pronounced intensity changes are observed for faint lines. Temporal changes in the behavior of the line fluxes have been observed on occasions (e.g., Bailey and Ward, 1981; Visvanathan and

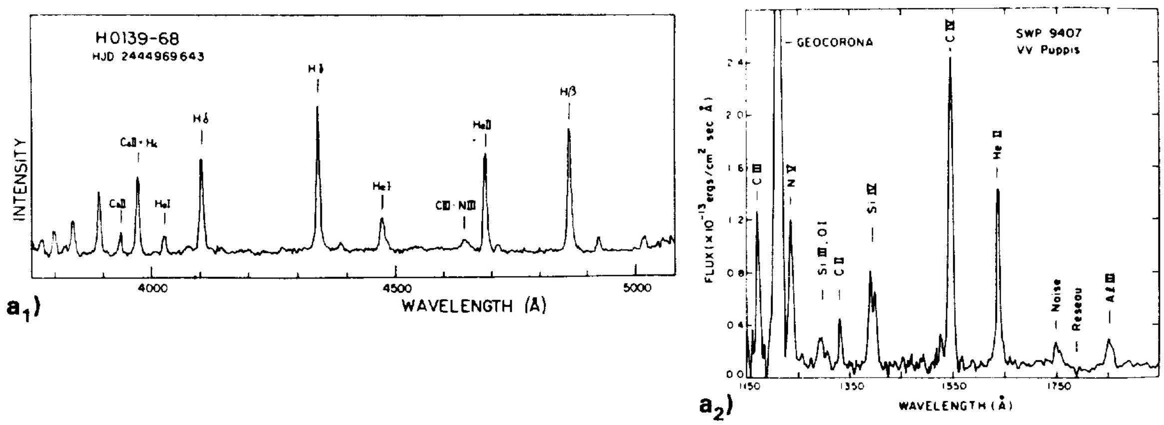


Figure 3-61. (a) Optical (Thorstensen et al, 1983) and (b) UV spectra of AM Her stars (Patterson et al, 1984).

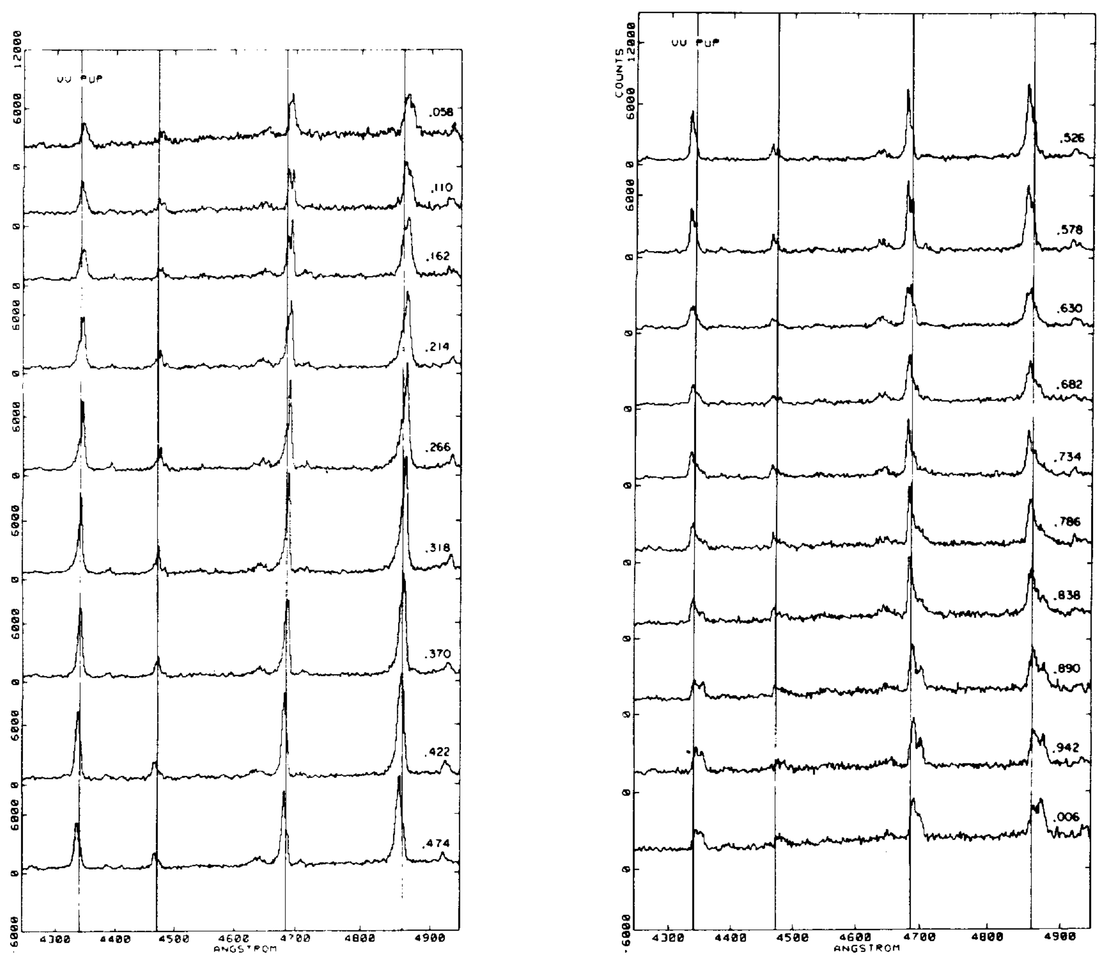


Figure 3-62a. Orbital spectrum changes in VV Pup (Schneider and Greenstein, 1980).

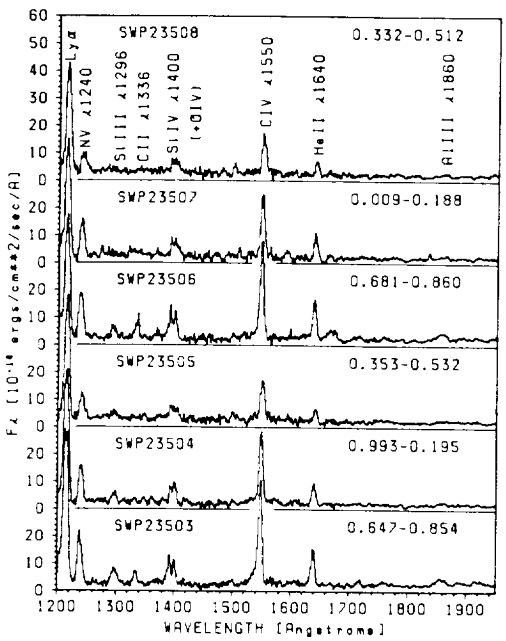


Figure 3-62b. Orbital Spectrum changes in QQ Vul (Mukai et al, 1986).

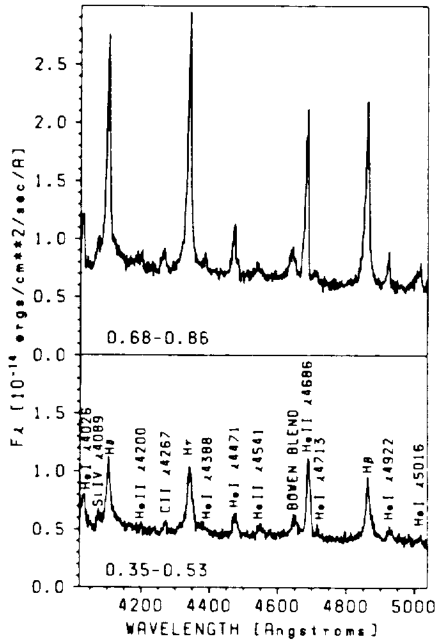


Figure 3-63. Changes in the line flux between high and low states in QQ Vul (Mukai et al, 1986).

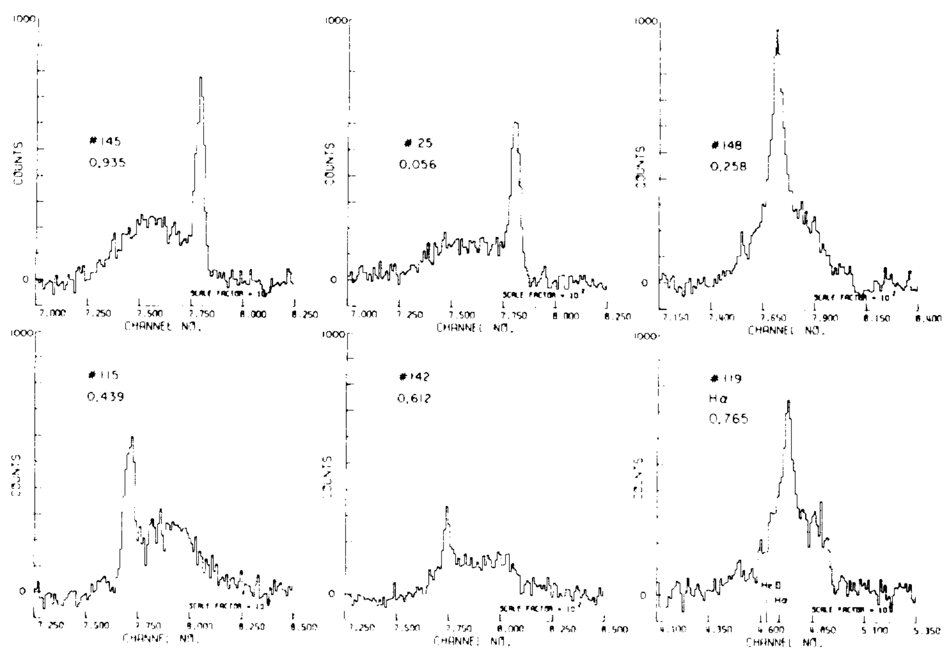
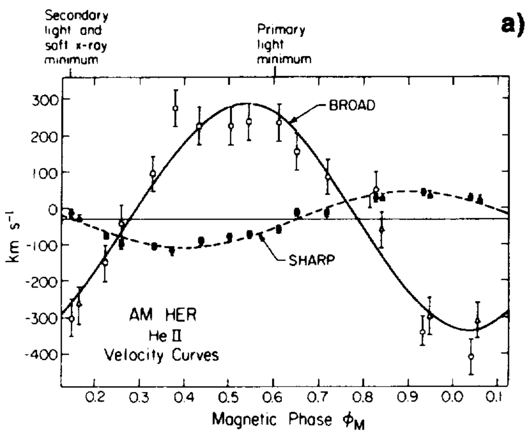


Figure 3-64. Broad and narrow line components in AM Her (Greenstein et al, 1977).

Wickramasinghe, 1981; Cowley et al, 1982; Mukai et al, 1986), indicating that the drop in intensity probably is not due to an eclipse by a stellar object, the confinements of which should be stable over long times.

Not only the line intensities, but even more the line profiles undergo marked complex, S-wave-like changes synchronous with the orbital cycle (Liebert et al, 1982a). In most, though not all, AM Herculis stars, both the



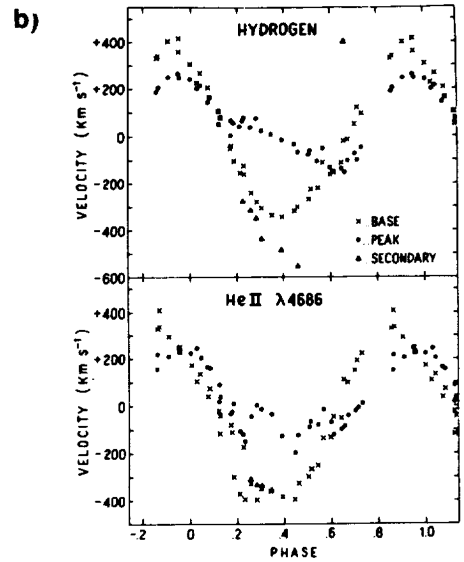


Figure 3-65. Radial velocities of AM Her at various epochs (a: Greenstein et al, 1977, b: Cowley and Crampton, 1977).

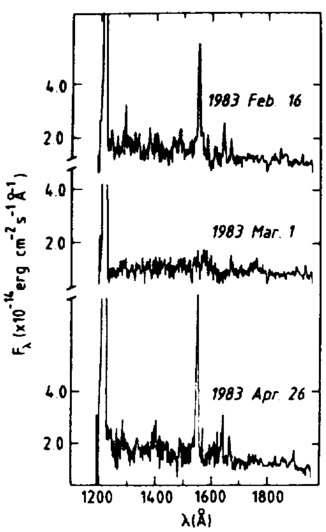


Figure 3-66. Spectral changes between high and low states in V834 Cen (Maraschi et al, 1984).

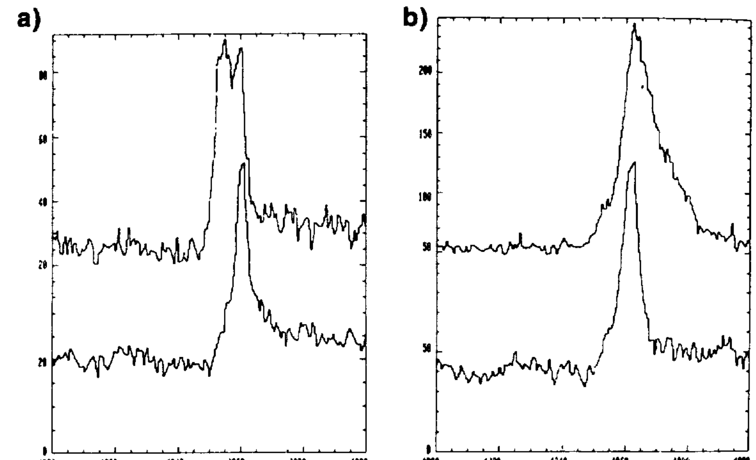


Figure 3-67. (a) Line profiles of AM Her in the low state at magnetic phases 0.58 and 0.60. (b) Spectra taken 0.09 orbital phases apart during a strong flare event (Latham et al, 1981).

Balmer lines and He II 4686 Å in particular consist of two components: a broad base component, stretching out to almost ± 1000 km/sec Doppler velocity, and a narrow sharp peak component (Figure 3-64) - often even more components can be distinguished (e.g., Rosen et al, 1987). In addition, the peak component can appear with a double-peaked structure at some orbital phases, but a single peak at other times, as the example of VV Pup in Figure 3-62a shows. The radial velocities of both peak and narrow components are different in K and γ-velocity as well as in orbital phasing (Figure 3-65). Usually the broad base has the larger velocity amplitude. The degree of phase lag is different for each object; for instance, it is almost zero for BL Hyi, 25% for EF Eri, 53% for VV Pup, and 133% for AM Her (Schneider and Greenstein, 1980; Thorstensen et al, 1983. As the example of AM Her in Figure 3-65 shows, however, this also seems to be subject to long-term changes. Similarly, as shown in Figure 3-65, velocity phases and amplitudes are different for different sorts of emission lines.

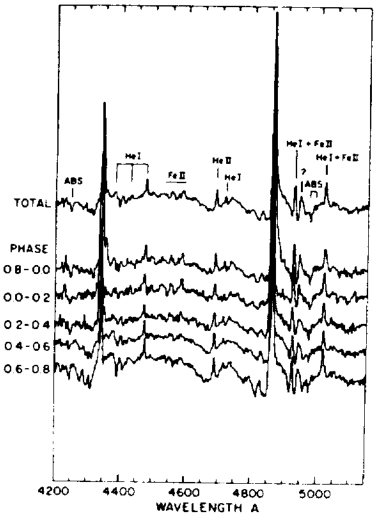


Figure 3-68. Cyclotron absorption features in AM Her (Latham et al, 1981).

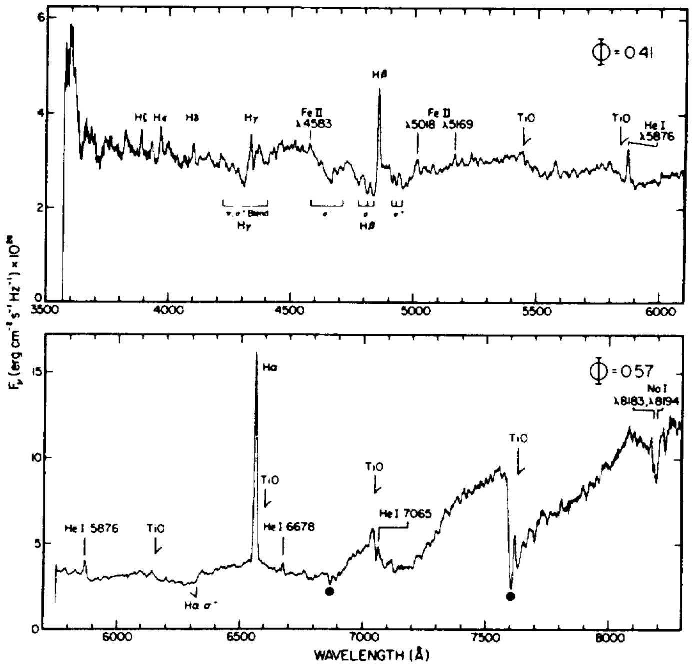


Figure 3-69. Secondary spectrum in AM Her in the low state (Schmidt et al, 1981).

During the optically high state, no stellar absorption features, as ascribed to the secondary star and often visible in other cataclysmic variables, can be detected with certainty.

Changes in the line spectra are related to changes in the systems between high and low states. The continuous flux distribution becomes even flatter, and emission lines are either weakened or disappear altogether. In ST LMi the UV radiation is hardly affected, whereas all emission lines disappear in V834 Cen (Figure 3-66). The broad base components which are visible during optically high states disappear. The He and metal lines usually are not visible any longer.

The radial velocities of the narrow H emissions follow almost the same pattern as those of the narrow components seen during high state, though they can be slightly out of phase. During one night an additional emission component of the H lines was visible in AM Her; this was much broader than the emission, reminiscent of the broad base during high state, though the radial velocities did not correspond to those seen during the brighter phase (Figure 3-67).

In all AM Herculis stars that have been observed during an optically faint state, complex absorption features are visible at the short and long wavelength sides of the H emission lines. Those features are only slightly variable with the orbital phase (Figure 3-68). In all cases they have been identified with Zeeman absorption features originating from magnetic fields with a strength of some 10 - 20 MG.

In some objects, the continuum flux increases considerably longward of about 5000 Å — like in other cataclysmic variables — and absorption bands of TiO and the Na I resonance lines at 8183 and 8194 Å become visible, indicating the presence of an M dwarf secondary (Figure 3-69; see also Mukai and Charles, 1986; 1987).

GENERAL INTERPRETATION: The white dwarfs in AM Herculis systems have strong magnetic fields, strong enough to entirely prevent the formation of *an accretion disc in the systems. Material spilled over from the secondary star is funneled directly onto the magnetic poles of the primary star; the gravitational energy is liberated in standing shocks right above the poles, which are the source of most of the observable photometric, polarimetric, and spectroscopic phenomena. Photometric and polarimetric light curves change in appearance when for some reason the position of the accretion poles on the surface of the white dwarf changes. A temporary decrease of mass overflow from the secondary star leads to low brightness states.*

OBSERVATIONAL CONSTRAINTS TO MODELS:

- *AM Herculis stars exhibit very strong linearly and circularly polarized radiation. (See 188)*
- *Temporal variations of the photometric, polarimetric, and spectroscopic appearance occur in phase at all wavelengths. (See 188)*
- *Occasionally the systems' flux can drop by several magnitudes. (See 188)*
- *In two systems (AM Her and QQ Vul) the total flux distribution was observed to change appreciably; in this "reversed mode" the X-ray light curves of both objects looked rather similar.*
- *The optical line profiles have a very complex structure in which several independently varying components can be identified.*
- *In the low states, Zeeman absorption features appear next to the emission lines. (See 188)*

VI. AM CANUM VENATICORUM STARS

The class of *AM Canum Venaticorum stars* so far consists of four members only: AM CVn (= HZ29), GP Com (= G61-29), PG 1346+082, and V803 Cen. Their most characteristic features are the total absence of hydrogen in their spectra, colors which are typical of cataclysmic variables, and extremely short photometric and/or spectroscopic periods.

VI.A. PHOTOMETRIC OBSERVATIONS

ABSTRACT: Photometric light curves are highly variable, displaying a sine-shaped appearance with two almost equal parts in the high brightness states and a more irregular appearance in the lower states. Strong flickering and at times quasi-periodic oscillations are present.

other nova-like stars: 96, 98, 102, 103, 106, 113, 114, 117, 119, 122, 125

dwarf novae: 35, 46

interpretation: 178

Photometrically, the most extensively observed AM Canum Venaticorum star is AM CVn itself. A part of its light curve is shown in Figure 3-70a. At approximately regular intervals of some nine minutes, photometric minima with a depth of typically 0.2 to 0.4 mag repeat; occasionally every other minimum is absent, or for a while no minimum can even be detected at all (Smak, 1975; Patterson et al, 1979; Solheim et al, 1984). Strong flickering on time scales of 20 sec to 5 min, which in amplitude can exceed the periodic photometric variations, is superimposed on the light curve.

There have been arguments over what the photometric period of this system would be. The occasional disappearance of every other minimum, and at the same time the usually relatively strong appearance of the remaining ones led to the conclusion that the 18 minute periodicity might be the orbital period. Assuming this to be the case, the secondary minimum would be placed at phase 0.54. Still, the periods change slightly at random about some mean value which is referred to as "phase jitter" (Patterson et al, 1979). However, it is not entirely clear that it is always the same minimum (eclipse) which is seen strongly, which then leads to aliases in period counting (Patterson, 1979; Solheim, 1984). Extensive analysis of all available photometric observations of AM CVn lead to the conclusion that the main photometric period is 0.0121648423 d — or half of it — and a period decrease of (-1.6 ± 0.03)

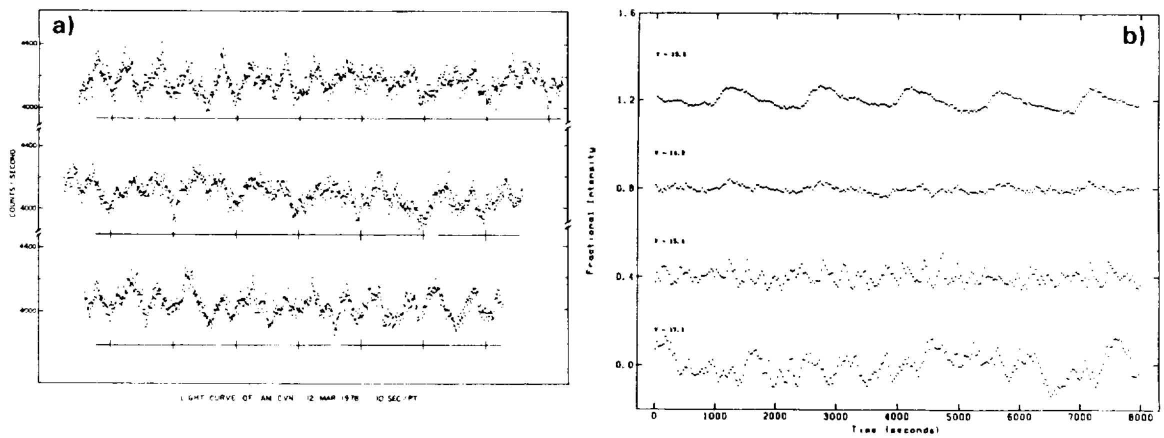


Figure 3-70. Optical light curves on orbital time scales of (a) AM CVn (Patterson et al, 1979) and (b) PG 1346 + 082 (Wood et al, 1987) at various brightness levels.

10^{-12} sec^{-1}. Superimposed on this development is a cyclical, but not strictly periodic, increase and decrease of the photometric period (Solheim, 1984).

Periodogram analysis of AM CVn at higher frequencies carried out by Warner and Robinson (1972) revealed the existence of photometric variations reminiscent of transient quasi-periodic oscillations with periods of 121, 118.9, 112.8, and 115.5 sec on three different occasions. The oscillations do not seem to be monochromatic, and during one night two periods were present simultaneously in one run both, however, might be an artifact due to too coarse a time resolution, similar to results in dwarf novae, where quickly shifting monochromatic oscillations are observed which could not be resolved in a coarse time resolution.

AM CVn so far only was seen at brightness levels around 14^m, and GP Com around 16^m. The other two Canum Venaticorum stars, V803 Cen and PG1346 + 082, are known to undergo brightness changes of some 4 mag amplitude (Wood et al, 1987; O'Donoghue et al, 1987). In PG1346 + 082, appreciable changes in the appearance of the light curve are connected with the overall brightness changes (Figure 3-70b): during the high state the light curve is reminiscent of that seen in AM CVn; as the light level decreases it becomes more and more irregular. Rather stable, though not totally coherent, oscillations with periods of several hundred seconds and some 25 minutes were found in all objects except for GP Com.

GP Com has been reported by Warner (1972) to show rapid irregular photometric variability. Nather et al (1981) observed the star on several occasions, but found hardly any photometric changes at all.

VI.B. SPECTROSCOPIC OBSERVATIONS

ABSTRACT: No trace of H can be detected in the spectra of AM Canum Venaticorum stars.

other nova-like stars: 99, 107, 114, 117, 119, 122, 134

dwarf novae: 65

The spectra of all AM Canum Venaticorum stars are similar in that none of them shows any trace of hydrogen. In the optical, very strong broad helium lines dominate; no hydrogen and hardly any lines of other elements can be found. In AM CVn, and in PG 1346 + 082 and V803 Cen during the high states, all lines are in absorption, in the latter two during low states; and in GP Com they are in emission (Figure 3-71; see also Robinson and Nather, 1975; Westin,

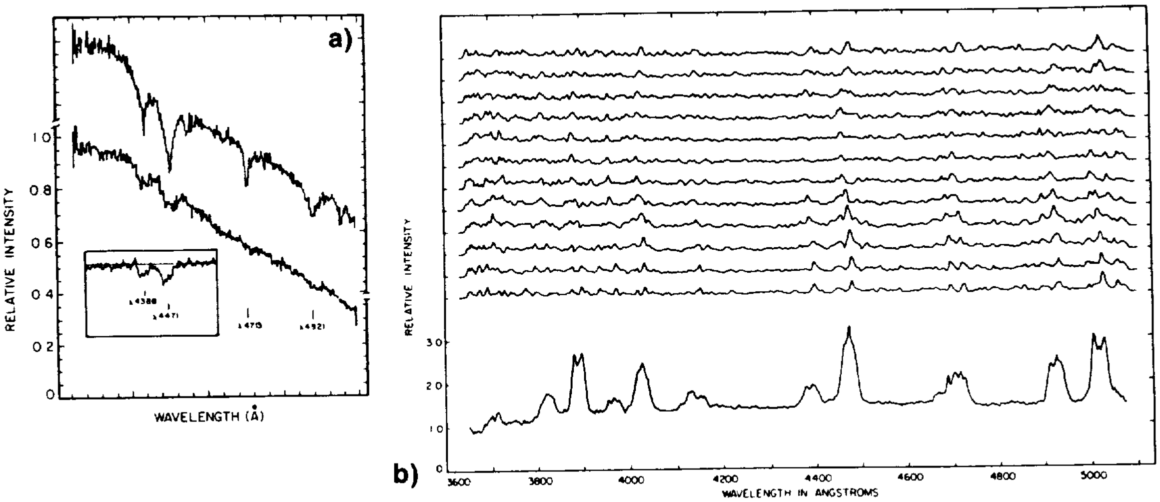


Figure 3-71. Optical spectra of (a) PG 1346+082 (lower spectrum) and AM CVn (insert); in the top panel the spectrum of a He white dwarf is displayed for comparison (Nather, 1985); (b) GP Com (Nather et al, 1981).

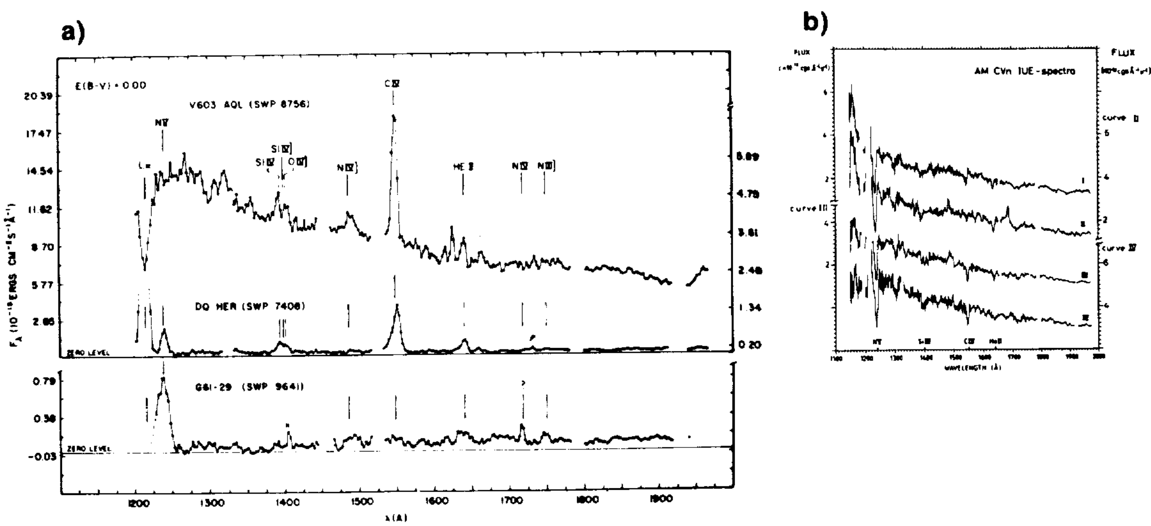


Figure 3-72. UV spectrum of (a) GP Com (=G61-29) (Lambert and Slovak, 1981) and (b) AM CVn (Solheim and Kjeldseth-Moe, 1987).

1980; Wood et al, 1987; O'Donoghue et al, 1987). In no case do the spectra resemble those of He white dwarfs (see Figure 3-71a) and, as Robinson and Nather point out, the ratios of He line strengths in AM CVn (and thus also in PG1346+082) and the remarkably asymmetric profiles are rather abnormal, not at all like what is expected in "normal" stars.

Time-resolved spectroscopic observations were carried out on GP Com (Nather et al, 1981). They find that the radial velocities measured from the wings of the emission lines lead to an orbital period of 46.52 min. Between the blue and red peaks a third narrow S-wave component clearly can be seen to migrate back and forth with the orbital period (Nather et al, 1981).

In the UV spectrum of GP Com (Figure 3-72a), NV 1240 Å is strongly in emission, He II 1640 Å is clearly present, N IV 1790 Å, N

IV] 1486 Å, and N III] 1750 Å are probably present. There is no trace of C IV 1550 Å, which in all other cataclysmic variables is the strongest or at least one of the strongest lines in the UV. The UV spectrum of AM CVn (Figure 3-72b), on the other hand, does not look abnormal for a cataclysmic variable: the normally strong lines like C IV, Si IV, and He II are all seen strongly in absorption; the lines are symmetric with no traces of mass out-flow.

GENERAL INTERPRETATION: These systems are currently understood to be cataclysmic variables consisting of a pair of white dwarfs.

OBSERVATIONAL CONSTRAINTS TO MODELS:

- *The orbital periods of AM Canum Venaticorum stars are decidedly shorter than those of all other cataclysmic variables.*
- *No hydrogen can be found in the spectra.*
- *These stars are not known to show any outburst activity. (See 178)*